THE IMPLICATIONS OF CHEMICAL CONTAMINATION IN FOOD: A SURVEILLANCE AND PROBABILISTIC HUMAN HEALTH RISK ASSESSMENT OF HEAVY METAL ACCUMULATION IN FOOD

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DECLARATION

DECLARATION WITH REGARD TO INDEPENDENT WORK

I, Kgomotso Lebelo, identity number (______________) and student number (_________), do hereby declare that this research report is my work. It is submitted for the Doctor of Philosophy degree in Environmental Health at the Central University of Technology, Free State. It has not been submitted before for any degree or examination at this or any other university.

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ABSTRACT

Food safety risks remain paramount in designing effective detection and surveillance systems. The globalisation of trade and environmental factors play a significant role in safeguarding against emerging and existing food safety risks from the food production chain to the consumer level. Targeted and routine human health risk assessments are critical in measuring exposure amongst populations. The study of chemical toxicity in the food industry is fundamental and needs to be supported by rigorous toxicological studies. This will improve the quality of food products offered by the food industry and ultimately benefit consumers. Contaminants such as heavy metals can cause adverse human health effects and thus need regulation through adequate legislative interventions and proper monitoring standards supported by curated scientific data. The study aimed to review the key drivers of chemical pollutants influencing contamination in food and their applicable surveillance methods. Then, measure the heavy metal contamination in the Bloemfontein fresh-produce markets. In this study, the first step in the research process included the extensive review of literature which aimed at establishing foundational information based on existing research. This was achieved through a rigorous literature review which framed the research questions and objectives. This study applied an experimental research strategy and encompassed a quantitative research method. Trace metal assessment was carried out in eighteen vegetable samples of six different vegetable types namely: *Spinacia oleracea*, *Beta vulgaris*, *Daucus carota*, *Allium*, *Brassica oleracea*, and *Solanum Lycopersicum*. The Inductively Coupled Plasma Optical Emissions Spectrometer (ICP-OES) was used to determine the concentration of heavy metals in selected vegetables, then measured against the *Codex Alimentarius* standards for metals in foodstuffs. In addition, probabilistic human health risk assessments were conducted to determine the hazard quotient and hazard index for the non-carcinogenic effects of the selected vegetables. Literature enquiry revealed that the food industry has been gravitating towards using mechanised systems with intelligent algorithms to meet the demand for safe food more cost-effectively. Therefore, the adoption of intelligent systems has shown significant benefits in controlling potential contaminants, thus reducing the burden of disease and economic loss. Findings further revealed that bioremediation studies should be intensified to cover a broad spectrum of contaminants such as heavy metals, pesticides, fertilizers, antibiotics, and microbial contaminants. As such, it should also consider the remediation of biological contaminants at the points of food production, processing, and supply chain. The concentration of cadmium in spinach, tomato, cabbage, and onion was reported to exceed the maximum permissible limits set by the *Codex*

Alimentarius for metals in foodstuffs. However, the estimated daily intake and hazard quotients were less than a unit. Moreover, the hazard index shows that none of the studied metals (As, Cu, Pb, Cd) had values greater than 1. This demonstrated that there are no anticipated adverse health effects. The Target Hazard Quotient (THQ) in order of exposure for all vegetable types was ranked as follows: As > Cd > Cu > Pb. Based on the findings of this study, precautions should be taken to control the accumulation of cadmium in spinach, tomato, cabbage, and onions due to potentially adverse effects. Most developing nations rely on agricultural produce; therefore, there must be investments in sustainable technologies and research to understand and predict the leading food contaminants. Future studies will incorporate more essential and non-essential metals in the analysis. Additionally, vegetable samples will be collected directly from agricultural land which is the beginning of the food production chain. Toxicological studies are known to be sensitive and difficult due to timelines. This creates a challenge regarding the correlation between chemicals and human health outcomes through epidemiological investigations to assess the risks. To date, no significant study apart from laboratory-controlled research yields any substantial results concerning human exposure and health outcomes. Therefore, there are still gaps regarding the types of chemical toxicants and their subsequent human health effects. This calls for rapid policy adoption on persistent pollutants due to the lack of immediate results of human health deterioration.

RESEARCH OUTPUTS

Published journal articles and book chapters:

1. Chemical contamination pathways along the various stages of food production: A review (2021). https://doi.org/10.3390/ijerph18115795
2. The prediction of food contamination and related diseases using intelligent systems: A Bibliometric analysis (2021), British Food Journal. https://www.emerald.com/insight/content/doi/10.1108/BFJ-04-2021-0366/full/html
3. The environmental impact of municipal solid waste and the application of biosurfactants in the bioremediation of polluted environments (2021), Elsevier. https://doi.org/10.1016/B978-0-12-822696-4.00017-6

Manuscripts under review:

1. The application of bioremediation techniques in food production and food safety (*Accepted book chapter, Bentham publishers*).
2. An overview of food contamination, detection, and surveillance: current and future trends, Scientific African, Elsevier, (Under review)
3. Microplastic contamination and its impact on food safety and associated health effects (2022), Heliyon, (Under review)
4. Compliance sampling and monitoring of heavy metal accumulation in selected vegetables using ICP-OES: A probabilistic human health risk assessment. Scientific African, Elsevier. (Under review)

DEDICATION

This thesis is dedicated to my family and those who mentored me in my career and personal development, but most importantly, to God Almighty for his eternal wisdom and guidance throughout this journey.

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LIST OF ABBREVIATIONS

ANNs	Artificial Neural Networks
CDC	Centre for Disease Control
CDI	Chronic Daily Intake
DAFF	The Department of Agriculture
DNNs	Deep Neural Networks
DoH	Department of Health
DTI	Department of Trade and Industry
EDI	Estimated Daily Intake
EHP	Environmental Health Practitioner
FBD	Foodborne Diseases
FMCs	Food Contact Materials
HI	Hazard Index
HQ	Hazard Quotient
ICP-OES	Inductively coupled plasma optical emission spectrometry
MPs	Microplastics
MSWN	Municipal solid-waste management
SEM-EDS	Scanning Electron Microscopy with Energy Dispersive X-Ray Spectrometer
THQ	Total Hazard Quotient
WHO	World Health Organization
WoS	Web of Science

CHAPTER 1: AN INTRODUCTION TO THE ROLE OF ENVIRONMENTAL HEALTH IN THE CONTROL OF ENVIRONMENTAL POLLUTION

The purpose of this chapter is to introduce the concept of food safety in terms of the role of Environmental Health and chemical contamination sources. This chapter will further give a brief overview of the pollution caused by heavy metals, toxicological properties within the food industry and potential consequences on the economy. This section provides context to the rationale behind the study and the approach used to formulate the key research themes and concepts. In addition, the aim and objectives are stated to justify the research project and its significance in the discipline of Environmental Health.

1.1. Background

Foodborne diseases are a long-standing global concern. These challenges are established even in developed countries. The devastating impact is felt predominantly in underdeveloped nations with ailing policies and infrastructure. Despite the well-recorded statistics in the global context, in Africa South Africa remains one of the inefficient nations regarding surveillance activities. These inefficiencies were highlighted in the 2017 Listeriosis outbreak in South Africa. The burden of disease outbreaks and food contamination investigations is primarily put on Environmental Health Services. Environmental Health Practitioners (EHPs) play an active role in food contamination and foodborne disease surveillance. Thus, they are custodians of food control and disease prevention as per the National Department of Health mandate. An effective disease surveillance system is categorized by services that meet the healthcare needs of the population it serves (Lebelo and Van Wyk, 2019; Lebelo, Masinde, *et al.*, 2021). Furthermore, it plays a significant role in healthcare service delivery, as it requires ongoing data collection, analysis and distribution of information that guide public health planning and intervention. Foodborne disease surveillance is fundamental in modern-day society, as it involves multiple stakeholders with varying practices and expertise such as EHPs. The degree of effort put into detecting diseases varies from one health worker to the next, thus influencing the quality of data obtained. This leads to the claim that practices applied in disease surveillance and routine monitoring can affect the outcome of many factors, such as resource allocation and even the magnitude and severity of the problem. It is therefore important to study surveillance tools so that gaps can be identified in addressing food contamination and effective methods of surveillance (NICD, 2015).

1.2. Food control departments and the gaps

South Africa has three core divisions or departments mandated to address the food control function in the republic: the Department of Agriculture, Forestry, and Fisheries (DAFF), the Department of Health (DoH), and the Department of Trade and Industry (DTI). The leading regulatory authority in charge of food security concerning agricultural products is DAFF. The DoH is mandated to handle foodstuffs, whilst DTI through the National Regulator for Compulsory Specifications (NRCS) is responsible for canned meat and meat products, canned and frozen fish, and accessing markets on a sustainable basis (Department of Health, Department of Trade and Industry and Department of Agriculture, 2013). These joint efforts in food control pose challenges regarding legal mandates and the designation of tasks. The three mentioned departments have major challenges in sharing resources and communicating key findings while responding to rapidly changing practices within the food industry.

1.3. Food control as a function of Environmental Health

Environmental Health Practitioners are mandated by law to monitor diseases of public health importance in South Africa. This is mandated by the regulations governing the scope of practice for Environmental Health promulgated under the *Health Act 61 of 2003* (National Department of Health, 2004). As stipulated in the regulations relating to their scope of practice, their functions according to Section 2 are as follow:

- Assisting in the sampling of foodstuffs for microbiological and chemical purposes and the collection of preliminary food, milk, cholera swabs and cooking oil indicator samples for non-forensic analysis.
- Conducting health education programmes for food handlers regarding personal hygiene, sanitizing of food contact surfaces and cleaning procedures and methods, and the prevention of food contamination from sources such as soil, water, air plants, animals and humans.
- Assisting in foodborne illness investigations.
- Assisting in sampling foodstuffs sold by informal traders.

- Carrying out surveys of both formal and informal food trading enterprises for statistical purposes.
- Assisting in the seizure, removal, detention, and proper disposal of unsafe foodstuffs.

The functions above outline the specific functions of EHPs in the surveillance of communicable diseases. As stated by Lebelo and Van Wyk (2019), "understanding environmental conditions in any given area of operation", Environmental Health Practitioners should be able to forecast sources of diseases and design control measures according to the specific needs of the affected community or industry.

1.4. Fundamentals of food safety

Studies have been conducted over the years explaining food safety and its impact on health outcomes and the economy. Researchers (Bennett *et al.*, 2020, Ali *et al.*, 2019) have asserted that food safety is a scientific subject that describes how to handle, prepare, and store food in a way that prevents food poisoning. Therefore, contamination and adulteration of food in various stages of the food chain might compromise food safety. It is widely reported that unsafe food causes a variety of acute and chronic illnesses, ranging from diarrhoea to various cancers (Gallo *et al.*, 2020). Ali and colleagues (2019) assert that food safety is a human right (Ali *et al.,* 2019). The authors further explain that hundreds of millions of people around the world are at risk of consuming contaminated food. Every year, multitudes of people become ill, and further thousands die due to contaminated food (Mehlhorn, 2015; Ali *et al.*, 2019). Literature has revealed that food safety enhances economic growth in areas where it is applied and improved (Bennett *et al.*, 2015; Tchatchouang *et al.*, 2020).

1.5. Heavy metal contamination in food, the underrated silent killer

Whilst the focus has primarily been on the surveillance of contamination caused by microorganisms in food, other factors are silent yet equally detrimental. Chemical contamination in food has devastating effects on human health, the economy and the environment in general (Lebelo, Malebo, *et al.*, 2021; Niu *et al.*, 2021).

Heavy metal contamination has spread globally, especially in developing countries causing disruptions in the environment, and posing detrimental effects on humans (Wei *et al.*, 2020). The rapid growth of urbanization, land use changes and industrialization, mostly in developing nations with increased population explosion, has observed such effects. The diversity of environmental contaminants has increased exponentially with countless anthropogenic sources since the industrial revolution and economic globalization (Dotaniya *et al.*, 2018). Heavy-metal pollution can come from both natural and man-made sources such as mining, smelting and agricultural activities (Liu *et al.*, 2021). These activities are known to contaminate large areas globally. One of the most serious ecological problems is heavy-metal contamination of agricultural soil due to the recurrent use of untreated or inadequately treated effluent from industrial operations, including the use of chemical fertilizers and pesticides (Latif *et al.*, 2018). Heavy metals can accumulate in high concentrations in plants growing in polluted environments, posing a major health risk when consumed. Therefore, anthropogenic activities should be regulated and monitored to reduce the probability of contamination of food sources (Negi*et al.*, 2020).

The transfer of heavy metals from soil to plants and their subsequent consumption is the major exposure route for humans. Leafy vegetables can accumulate higher heavy-metal concentrations in the edible tissues than non-leafy vegetables (Bi *et al.*, 2018; Hashemi, 2018; Bagheri *et al.*, 2020). Soil is not the only contamination source of heavy metals in vegetables. In some instances, direct foliar uptake of atmospheric Pb and Hg is the dominant pathway for Pb and Hg accumulation (Kumar *et al.*, 2019; Cao *et al.*, 2022). Several hazardous heavy metals and metalloids, for example, arsenic (As), lead (Pb), cadmium (Cd) and mercury (Hg), are classified as non-essential to metabolic and other biological functions (Mandlate *et al.,* 2020; Lebelo, Malebo, *et al.*, 2021; Munir *et al.*, 2022). With the rapid development of urbanization, vegetable farms are often located close to heavy industrial areas, placing them at risk of being contaminated by local pollutants (Singh *et al.*, 2018; Munir *et al.*, 2022). Metals found as contaminants in vegetables include As Cd and Pb. These metals can cause a significant health risk to humans, especially in high concentrations above very low body requirements (Latif *et al.*, 2018). An excessive number of heavy metals in food cause several diseases, especially cardiovascular, renal, neurological and bone diseases (Latif *et al.*, 2018). Metals like arsenic, cadmium, lead and mercury are chemical substances that exist naturally. They can be found in a variety of places in the environment, including soil, water and the atmosphere (Thompson and Darwish, 2019; Munir *et al.*, 2022). Metals can also be found in food as residues due to their existence in the environment, human activities such as farming, industry or vehicle exhaust, or contamination during food processing and storage. These metals can be consumed or absorbed from the environment through contaminated food or water (Hou *et al.*, 2020).

1.5.1 Heavy-metal contamination studies in South Africa

South Africa is one of the countries rich in mineral resources. As a result, anthropogenic activities in the form of mining and other heavy industries introduce contamination to the environment. These high-density industrial parks are usually associated with increased population and an equal demand for resources in wastewater drainage systems, drinking water and food (Atangana and Oberholster, 2021). This increasing demand for water poses a risk because of the potential heavy-metal contamination and variation in surface and groundwater. Historical studies have shown empirical evidence through human health risk assessments that heavy metals pose risks to humans in polluted environments such as the Witbank area associated with coal pollution. These risks can be non-carcinogenic or carcinogenic when accumulated throughout the human lifespan. The exposure occurs through three exposure routes: ingestion, inhalation and dermal contact (Zerizghi *et al.*, 2022). Various studies in South Africa have been conducted to measure heavy metal content in medicinal plants (Malan *et al.*, 2012; Okem *et al.*, 2014), river streams (Jackson *et al.*, 2009), soil (Gzik *et al.*, 2003; Malan *et al.*, 2015) and vegetable gardens (Bvenura and Afolayan, 2012; Malan *et al.*, 2015). These studies highlight the lack of data and preliminary research to measure the extent of the pollution.

1.5.2. Heavy metals in the environment

Heavy metals are a core part of rocks and soils in the environment, and they are introduced through erosion, human activity, weathering of soil minerals, land application of treated wastewater (TWW), sewage sludge, fertilizers and industrial activities. Heavy metals can penetrate the soil and accumulate in the plant-human atmosphere (Niu *et al.*, 2020; Teresa *et al.*, 2021). The overall concentration of heavy metals in soil is equal to the total of these variables minus losses due to off-take in cultivated crops (Xiang *et al.*, 2021), erosion of soil particles by water or wind, leaching down the soil profile in solution, and losses due to volatilization of certain elements in gaseous forms (Kumar *et al.*, 2019).

Atmospheric deposition, livestock manure, irrigation with wastewater or contaminated water, Metallo-pesticides or herbicides, phosphate-based fertilizers, and sewage sludge-based amendments are the primary sources of heavy metals in the soil environment and agriculture (Maddela *et al.*, 2020; Mongi and Chove, 2020). Agriculture, industry, mining, transportation, fuel use, residual organic matter and sewage water are the major anthropogenic sources (López-

Pacheco *et al.*, 2019). Windblown dust, volcanic particles, forest wildfires, plants and sea salt are all major natural sources of heavy metals. Agricultural soil contamination occurs because of irrigation with wastewater and contamination by microplastics which can harbour these heavy metals (Kumar *et al.*, 2019).

1.5.3. The control of heavy metal contamination

Direct actions on plants and indirect actions on contamination sources such as physical, chemical and biological methods to clean up cultivated soils, irrigation water and air are two types of strategies for preventing toxic heavy metals from entering plant tissues and the food chain (Oves *et al.*, 2017; Rai *et al.*, 2019). Eliminating or detoxifying harmful heavy metals from the environment has played a critical role in phytoremediation (Kapahi and Sachdeva, 2019). This technique focuses on transgenic plants overexpressing particular genes involved in the uptake, translocation, sequestration and tolerance of various compounds (Koźmińska *et al.*, 2018). Genetic engineering and manipulation can be used to improve the inbuilt genetic potential and phytoremediation ability of potential plants, depending on the community's needs (Maiti and Pandey, 2020).

Heavy metals have been removed or recovered from polluted settings using a variety of approaches. Adsorption methods, chemical oxidation or reduction reactions, chemical precipitation, electrochemical approaches, evaporative recovery, ion exchange, reverse osmosis and sludge filtrate are some of the established conventional procedures for heavy-metal removal and recovery. Bioremediation is a cutting-edge indirect approach for removing and recovering heavy-metal ions from contaminated environments. It involves employing living organisms (algae, bacteria, fungi, or plants) to reduce and recover heavy-metal pollution into less harmful forms (Byers *et al.*, 2019; Kasozi *et al.*, 2021).

On strict and effective pollution source control, heavy-metal pollution of forest soil should be prevented and controlled at the source. Transportation, industrial operations, urban wastes and atmospheric precipitation are the main contributors to heavy-metal contamination. Non-point heavy-metal pollution in the environment is primarily caused by motor vehicle exhaust and dust generated by wearing tyres. Governments should make it mandatory for automobile owners to adopt clean energy and improve their handling of destroyed vehicles (Hejna *et al.*, 2018, 2021).

Governments should also strengthen the road traffic management system, prohibit road markets, avoid traffic congestion, and keep traffic flowing smoothly. Furthermore, throughout industrial production, clean production processes should be established. To avoid complex types of environmental contamination, governments should firmly apply the 'three-wastes' strategy, particularly the recovery and comprehensive application of heavy metals in the exhaust gas, waste residue and sludge. Small manufacturing plants that are unable to dispose of garbage properly should be shut down or sanctioned (Dai *et al.*, 2016).

1.6. Economic burden caused by contaminated food

Foodborne illness outbreaks can potentially be disastrous to the food industry or enterprise. A single outbreak of a foodborne illness might result in an unimaginable economic loss (Dallal *et al.*, 2020). Recently, there has been an increase in the globalized food trade, extensive production often involving many sites and a complex supply chain, all of which contribute to an increase in the number of microbiological food safety outbreaks. Furthermore, the volume of international food trade rises year after year. These factors can put tremendous pressure on food companies to be globally competitive, which can occasionally result in a negligent attitude towards food safety control by producers, resulting in a food scandal.

An economic analysis of food safety expenses revealed that it is much less expensive for a producer to invest in preventing foodborne outbreaks than it is to invest after someone has been exposed to the outbreak (Dallal *et al.*, 2020). Evaluating infectious disease control entails determining whether the absence of any illness possibly frees up resources that may subsequently be employed for other reasons. A comprehensive economic assessment of an epidemic would attempt to estimate and analyse the complicated network of activities, as well as evaluate their contribution. A thorough economic appraisal of an outbreak would seek to cost and analyse the intricate web of activities and value their contribution.

1.7. Research overview

The field of Environmental Health deals with exposures to both natural and built environments and their effects on human health. This branch of public health is often integrated and merged with various disciplines for effective interventions. In this study, public health principles will be merged with chemical engineering tools and laboratory analytical techniques as part of surveillance activities that may be adopted by local governments in the detection of food contaminants. This project has different sections, ranging from the *status quo* of food control surveillance, chemical contamination pathways in the food chain and risk assessment of heavy metals, and bioremediation techniques of polluted environments and their implications on food safety.

1.8. Problem statement

The best food-control surveillance systems are characterised by the rapid identification of disease causing-agents and possess predictive power to forecast food-related conditions that may be detrimental to people's health. Surveillance systems should be designed so that they provide timeous data to policymakers and stakeholders. As a result, it saves on the cost burden associated with rendering health services after the fact. The surveillance of chemical contamination in food allows public health professionals to make informed decisions and allocate resources on time. Furthermore, it provides a platform for human-health risk assessments concerning various environmental contaminants, which are prevalent in the food industry. The current food control system in South Africa regarding chemical contamination is reactive. One of the leading factors of this reactive system is the lack of capacity for rapid surveillance and predictive tools. Current trends in the food industry suggest that more contamination is probable, considering the lack of monitoring and laboratory capacity in the detection of chemical contaminants, such as essential and non-essential heavy metals. Failure to implement surveillance tools and human-health risk assessments on chemical contamination and rapid response will result in the collapse of the public health system, especially regarding the identification, surveillance, and control of possible contaminants.

1.8.1. Aim

The study aimed to review the literature relating to factors influencing chemical contamination in food and surveillance methods and then to measure the heavy metal contamination in Bloemfontein fresh-produce markets using ICP-OES. Furthermore, a human-health risk assessment had to be conducted to determine the hazard quotient and hazard index for the non-carcinogenic effects of the selected vegetables.

1.8.2. Hypothesis

Vegetables sold at Bloemfontein fresh-produce markets have heavy-metal concentrations exceeding the permissible limits as per the regulations on the maximum allowable limits for heavy metals in foods. As a result, the hazard quotients and hazard index will be ≥ 1.

1.8.3. Research questions

The proposed research will be guided by the following research questions:

- What is the concentration of heavy metals in selected vegetables in relation to maximum limits standards in South Africa?
- What are the toxicologic risk factors inherent to humans following exposure to heavy metals in vegetables?
- How efficient is the Inductively Coupled Plasma Optical Emissions Spectrometry (ICP: OES) method in detecting the contaminants in vegetables?

1.8.4. Objectives

The objectives of the study were to:

- Evaluate the current trends in food contamination research and surveillance techniques
- Discuss the chemical contamination pathways and their implications for food safety
- Discuss the chemical environmental pollutants and alternative bioremediation techniques in the food sector
- Determine the heavy-metal concentration of selected vegetables in the Bloemfontein fresh-produce markets
- Examine the toxicological effects of human exposure to heavy metals via vegetable intake
- Assess the applicability and efficiency of the Inductively Coupled Plasma Optical Emissions Spectrometry (ICP-OES) method as an option in a food-control model.

1.9. Significance and original contribution to knowledge

This study explored the gaps concerning chemical contamination in food with specific reference to heavy-metal accumulation in selected vegetables. The findings can further improve surveillance by designing tools that are efficient and specific to the food-control function in South Africa. Moreover, they will form part of a management system that will be used for public health planning and resource allocation. This study forms a platform for a better understanding of the remediation needs of polluted agricultural land and produce. It also provides engagement by industry and academia to explore essential topics in food contamination and toxicology.

1.10. Thesis structure

This thesis consists of ten chapters. Each chapter has a central theme related to the surveillance and chemical contamination factors affecting the food industry. The chapters are arranged logically to address critical issues surrounding the chemical contamination of food and prospective surveillance methods. The thesis culminates in potential control strategies and recommendations for effective surveillance and monitoring of heavy metal contamination in food. The chapter titles are listed in Table 1.1.

Table 1.1: Key themes in the thesis

Chapters	**Title**
1	An introduction to the role of environmental health in the control of environmental pollution
2	Methodology
3	The surveillance and prediction of food contamination using intelligent systems: A Bibliometric analysis.
4	An overview of food contamination, detection, and surveillance: current and future trends.
5	Chemical contamination pathways and the food safety implications along the various stages of food production: a review
6	The environmental impact of municipal solid waste and the application of biosurfactants in the bioremediation of polluted environments.
7	Microplastic and its impact on food safety and associated health effects.

8	Bioremediation of environmental contaminants and their impact on food safety in the food production chain.
9	Compliance sampling and monitoring of heavy metal accumulation in selected vegetables using ICP-OES: A probabilistic human health risk assessment.
10	A comprehensive overview of food contamination and surveillance in the South African food production chain: A narrative synopsis

1.11 References

Ali, H., Khan, E. and Ilahi, I. (2019) ‘Environmental chemistry and ecotoxicology of hazardous heavy metals: Environmental persistence, toxicity, and bioaccumulation’, *Journal of Chemistry*, 2019(Cd). doi: 10.1155/2019/6730305.

Atangana, E. and Oberholster, P. J. (2021) ‘Using heavy metal pollution indices to assess water quality of surface and groundwater on catchment levels in South Africa’, *Journal of African Earth Sciences*, 182. doi: 10.1016/j.jafrearsci.2021.104254.

Bagheri, M. *et al.* (2020) ‘Examining plant uptake and translocation of emerging contaminants using machine learning: Implications to food security’, *Science of the Total Environment*, 698, p. 133999. doi: 10.1016/j.scitotenv.2019.133999.

Bennett, S. D. *et al.* (2015) ‘Multistate foodborne disease outbreaks associated with raw tomatoes, United States, 1990-2010: A recurring public health problem’, *Epidemiology and Infection*, 143(7), pp. 1352–1359. doi: 10.1017/S0950268814002167.

Bennett, S. D. *et al.* (2020) ‘Produce-associated foodborne disease outbreaks , USA , 1998–2013’.

Bi, C. *et al.* (2018) ‘Heavy metals and lead isotopes in soils, road dust and leafy vegetables and health risks via vegetable consumption in the industrial areas of Shanghai, China’, *Science of the Total Environment*, 619–620, pp. 1349–1357. doi: 10.1016/j.scitotenv.2017.11.177.

Bvenura, C. and Afolayan, A. J. (2012) ‘Heavy metal contamination of vegetables cultivated in home gardens in the Eastern Cape’, *South African Journal of Science*, 108(9–10), pp. 1–6. doi: 10.4102/sajs.v108i9/10.696.

Byers, H. L., McHenry, L. J. and Grundl, T. J. (2019) ‘XRF techniques to quantify heavy metals in vegetables at low detection limits’, *Food Chemistry: X*, 1(March 2018), p. 100001. doi: 10.1016/j.fochx.2018.100001.

Cao, C. *et al.* (2022) ‘Science of the Total Environment Crop selection reduces potential heavy metal (loid) s health risk in wastewater contaminated agricultural soils’, *Science of the Total Environment*, 819, p. 152502. doi: 10.1016/j.scitotenv.2021.152502.

Dai, S. Y. *et al.* (2016) ‘Heavy Metal Contamination of Animal Feed in Texas’, *Journal of Regulatory Science*, 01, pp. 21–32.

Dallal, S. *et al.* (2020) ‘Associations between climatic parameters and the human salmonellosis in Yazd province, Iran’, *Environmental Research*, 187, p. 109706. doi: 10.1016/j.envres.2020.109706.

Department of Health, Department of Trade and Industry and Department of Agriculture, F. and F. (2013) *Report food safety and food control in South Africa : specific reference to meat labelling Report from the Department of Health (DoH); Department of Trade and Industry (DTI) and Department of Agriculture, Forestry and Fisheries (DAFF)*. Pretoria. Available at: http://pmg-assets.s3-website-eu-west-1.amazonaws.com/130621food.pdf.

Dotaniya, M. L. *et al.* (2018) ‘Bioremediation of metal contaminated soil for sustainable crop production’, in Meena, V. (ed.) *Role of Rhizospheric Microbes in Soil*. Singapore: Springer Nature Singapore, pp. 143–165. doi: 10.1007/978-981-10-8402-7.

Gallo, M. *et al.* (2020) ‘Relationships between food and diseases: What to know to ensure food safety’, *Food Research International*, 137. doi: 10.1016/j.foodres.2020.109414.

Gzik, A. *et al.* (2003) ‘Heavy metal contamination of soils in a mining area in South Africa and its impact on some biotic systems’, *Journal of Soils and Sediments*, 3(1), pp. 29–34. doi: 10.1007/BF02989466.

Hashemi, M. (2018) ‘Ecotoxicology and Environmental Safety Heavy metal concentrations in bovine tissues (muscle, liver and kidney) and their relationship with heavy metal contents in consumed feed’, *Ecotoxicology and Environmental Safety*, 154(February), pp. 263–267. doi: 10.1016/j.ecoenv.2018.02.058.

Hejna, M. *et al.* (2018) 'Review: Nutritional ecology of heavy metals', *Animal*, 12(10), pp. 2156–2170. doi: 10.1017/S175173111700355X.

Hejna, M. *et al.* (2021) 'Heavy-metal phytoremediation from livestock wastewater and exploitation of exhausted biomass', *International Journal of Environmental Research and Public Health*, 18(5), pp. 1–16. doi: 10.3390/ijerph18052239.

Hou, D. *et al.* (2020) 'Metal contamination and bioremediation of agricultural soils for food safety and sustainability', *Nature Reviews Earth & Environment*. doi: 10.1038/s43017-020-0061-y.

Jackson, V. A. *et al.* (2009) 'Bioremediation of metal contamination in the Plankenburg River, Western Cape, South Africa', *International Biodeterioration and Biodegradation*, 63(5), pp. 559–568. doi: 10.1016/j.ibiod.2009.03.007.

Kapahi, M. and Sachdeva, S. (2019) 'Bioremediation options for heavy metal pollution', *Journal of Health and Pollution*, 9(24). doi: 10.5696/2156-9614-9.24.191203.

Kasozi, K. I. *et al.* (2021) 'An analysis of heavy metals contamination and estimating the daily intakes of vegetables from Uganda', *Toxicology Research and Application*, 5, p. 239784732098525. doi: 10.1177/2397847320985255.

Koźmińska, A. *et al.* (2018) 'Recent strategies of increasing metal tolerance and phytoremediation potential using genetic transformation of plants', *Plant Biotechnology Reports*, 12(1), pp. 1–14. doi: 10.1007/s11816-017-0467-2.

Kumar, S. *et al.* (2019) 'Hazardous heavy metals contamination of vegetables and food chain: Role of sustainable remediation approaches – A review', *Environmental Research*, 179, p. 108792. doi: 10.1016/j.envres.2019.108792.

Latif, A. *et al.* (2018) 'Heavy Metal Accumulation in Vegetables and Assessment of their Potential Health Risk', *Journal of Environmental Analytical Chemistry*, 05(01), pp. 1–7. doi: 10.4172/2380-2391.1000234.

Lebelo, K., Malebo, N. *et al.* (2021) 'Chemical Contamination Pathways and the Food Safety Implications along the Various Stages of Food Production : A Review', *International*

Journal of Environmental Research and Public Health, 18(11). doi: https://doi.org/10.3390/ijerph18115795.

Lebelo, K., Masinde, M. *et al.* (2021) 'The surveillance and prediction of food contamination using intelligent systems: a bibliometric analysis', *British Food Journal*. doi: 10.1108/BFJ-04-2021-0366.

Lebelo, K. and Van Wyk, R. (2019) 'Communicable disease Surveillance in the City of Ekurhuleni: Environmental Health Practitioners' perceptions', in *2019 Open Innovations Conference, OI 2019*, pp. 371–376. doi: 10.1109/OI.2019.8908191.

López-Pacheco, I. Y. *et al.* (2019) 'Anthropogenic contaminants of high concern: Existence in water resources and their adverse effects', *Science of the Total Environment*, 690, pp. 1068–1088. doi: 10.1016/j.scitotenv.2019.07.052.

Maddela, N. R. *et al.* (2020) 'Cocoa-laden cadmium threatens human health and cacao economy: A critical view', *Science of the Total Environment*, 720, p. 137645. doi: 10.1016/j.scitotenv.2020.137645.

Maiti, D. and Pandey, V. C. (2020) 'Metal remediation potential of naturally occurring plants growing on barren fly ash dumps', *Environmental Geochemistry and Health*, 0123456789. doi: 10.1007/s10653-020-00679-z.

Malan, M. *et al.* (2012) 'Heavy metal contamination in South African medicinal plants: A cause for concern', *Environmental Monitoring and Assessment*, 93(1), pp. 125–130. doi: 10.1016/j.ibiod.2009.03.007.

Malan, M. *et al.* (2015) 'Heavy metals in the irrigation water, soils and vegetables in the Philippi horticultural area in the Western Cape Province of South Africa', *Environmental Monitoring and Assessment*, 187(1), pp. 1–8. doi: 10.1007/s10661-014-4085-y.

Mehlhorn, H. (2015) 'Food-Borne Disease Burden Epidemiology Reference Group', *Encyclopedia of Parasitology*, 51(4), pp. 1–1. doi: 10.1007/978-3-642-27769-6_3884-1.

Mongi, R and Chove, L. (2020) 'Heavy Metal Contamination in Cocoyam Crops and Soils in

Countries around the Lake Victoria Basin (Tanzania, Uganda and Kenya)’, *Tanzania Journal of Agricultural Sciences*, 19(2), pp. 148–160.

Munir, N. *et al.* (2022) ‘Heavy metal contamination of natural foods is a serious health issue: A review’, *Sustainability (Switzerland)*, 14(1), pp. 1–20. doi: 10.3390/su14010161.

National Department of Health (2004) ‘National Health Act, No. 61 of 2003’, *Government Gazette*, 463(61). Available at: https://www.up.ac.za/media/shared/12/ZP_Files/health-act.zp122778.pdf [5 November 2018].

National Institute for Communicable Diseases *et al.* (2015) ‘Africa’s Health Burden: Assessing the Role of Community in Health Care Delivery’, *BMC Public Health*, 6(1), pp. 1–8. doi: 10.1186/1471-2458-4-29.

Negi, P., Mor, S. and Ravindra, K. (2020) ‘Impact of landfill leachate on the groundwater quality in three cities of North India and health risk assessment’, *Environment, Development and Sustainability*, 22(2), pp. 1455–1474. doi: 10.1007/s10668-018-0257-1.

Niu, B. *et al.* (2020) ‘Bioaccumulations and potential human health risks assessment of heavy metals in ppk-expressing transgenic rice’, *Science of the Total Environment*, 710(August 2020), pp. 339–346. doi: 10.1016/j.scitotenv.2020.137645.

Niu, B. *et al.* (2021) ‘Safety risk assessment and early warning of chemical contamination in vegetable oil’, *Food Control*, 125. doi: 10.1016/j.foodcont.2021.107970.

Okem, A. *et al.* (2014) ‘Heavy metal contamination in South African medicinal plants: A cause for concern’, *South African Journal of Botany*, 93, pp. 125–130. doi: 10.1016/j.sajb.2014.04.001.

Oves, M., Khan, M. Z. and Ismail, I. M. I. (2017) ‘Modern age environmental problems and their remediation’, *Modern Age Environmental Problems and their Remediation*, pp. 1–237. doi: 10.1007/978-3-319-64501-8.

Rai, P. K. *et al.* (2019) ‘Heavy metals in food crops: Health risks, fate, mechanisms, and management’, *Environment International*, 125, pp. 365–385. doi:

10.1016/j.envint.2019.01.067.

Tchatchouang, C. D. K. *et al.* (2020) ‘Listeriosis outbreak in South Africa: A comparative analysis with previously reported cases worldwide’, *Microorganisms*, 8(1). doi: 10.3390/microorganisms8010135.

Teresa, G. *et al.* (2021) ‘Chemosphere Heavy metal contamination and health risk assessment in grains and grain-based processed food in Arequipa region of Peru’, p. 274. doi: 10.1016/j.chemosphere.2021.129792.

Thompson, L. A. and Darwish, W. S. (2019) ‘Environmental Chemical Contaminants in Food: Review of a Global Problem’, *Journal of Toxicology*, 2019, pp. 1–14. doi: 10.1155/2019/2345283.

Wei, R. *et al.* (2020) ‘Bioaccumulations and potential human health risks assessment of heavy metals in ppk-expressing transgenic rice’, *Science of the Total Environment*, 710, p. 136496. doi: 10.1016/j.scitotenv.2020.136496.

Xiang, M. *et al.* (2021) ‘Heavy metal contamination risk assessment and correlation analysis of heavy metal contents in soil and crops *’, 278. doi: 10.1016/j.envpol.2021.116911.

Zerizghi, T. *et al.* (2022) ‘An integrated approach to quantify ecological and human health risks of soil heavy metal contamination around coal mining area’, *Science of the Total Environment*, 814, p. 152653. doi: 10.1016/j.scitotenv.2021.152653.

CHAPTER 2: METHODOLOGY

2.1. Introduction

This chapter aims to outline the steps taken to achieve the research objectives. It focuses on the research design and the critical procedures undertaken to justify the goals of this study. This chapter covers the methodological theories and experimental processes in line with the stated objectives in Chapter 1.

2.2. Research philosophy and paradigm

This research project is underpinned by a philosophical worldview and assumption that motivated the need for scientific enquiry. This study followed a deductive reasoning research approach. This approach assisted the researcher to limit bias, make specific conclusions and provide replication of research results (Kim and Steiner, 2016; Khaldi, 2017). Moreover, the positivist perspective was employed to analyse the experimental results objectively (see Figure 2.1). The postpositivist paradigm holds for quantitative studies, more than qualitative investigations (Marczyk *et al*, 2005; Jackson, 2009; Cresswell, 2016). This paradigm aims to test, verify and refine the causes that influence outcomes often completed using experiments.

2.3. Research design

Researchers have stated that three approaches (quantitative, qualitative, and mixed methods) to research must never be viewed as discrete and rigid; instead, they should be viewed as part of a continuum (Johnson and Christensen, 2014; Cresswell, 2016). This study followed a quantitative approach, as influenced by the definition of John W. Cresswell, who states that quantitative studies typically test objective theories by investigating variables (Cresswell, 2016). These variables can be measured using statistical procedures (Azevedo *et al.*, 2011; Ferreira *et al.*, 2017; Leatherdale, 2019).

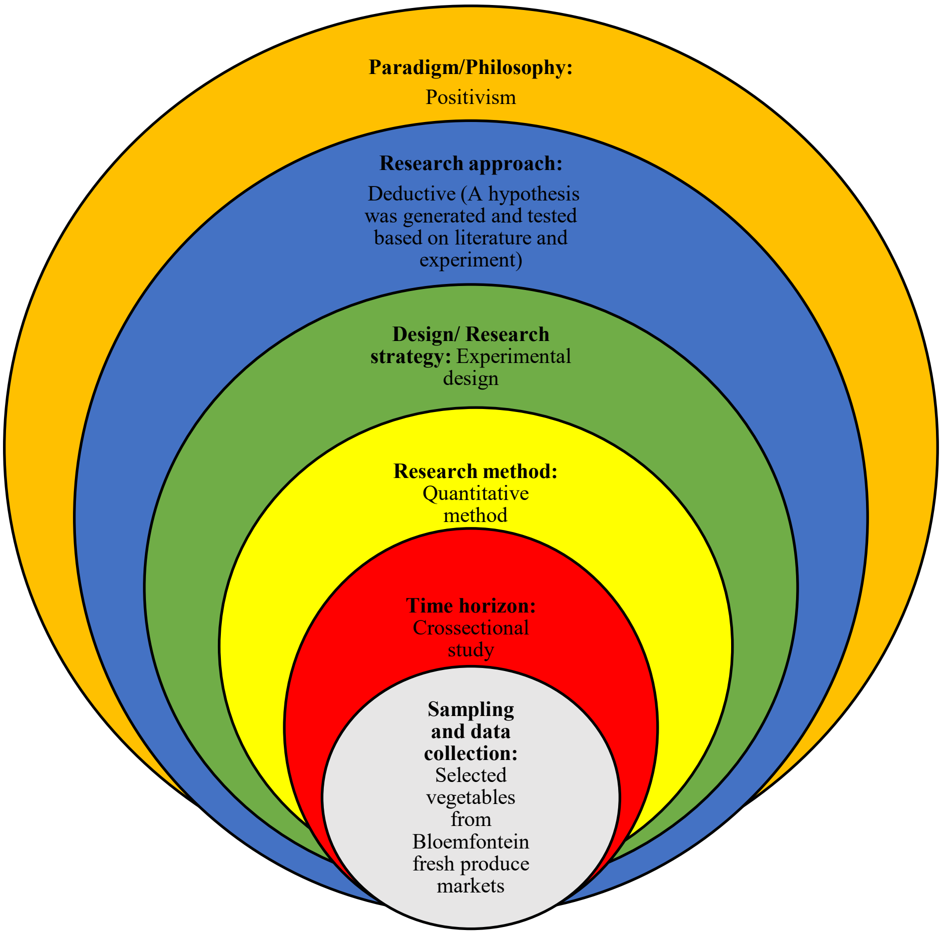


Figure 2.1: Summary of the research approach. The multiple layers represent the philosophical thought process and methodological choices of the researcher.

The first step in the research process included an extensive literature review which aimed at establishing a foundation for academic investigation. As influenced by Xiao and Watson's study, the fundamental principle in this study was to advance knowledge based on existing research (Xiao and Watson, 2019). This was achieved through a rigorous literature review to understand the existing body of work to frame the research questions and objectives. As recommended by different scholars, the review of the literature was methodologic and encompassed strict search criteria of research papers, i.e. original research, reviews, conference proceedings, books, etc. (Leatherdale, 2019; Xiao and Watson, 2019). The main databases in literature identification were Google Scholar and the Web of Science (WoS). The review papers included in this study give context to the empirical research conducted; however, they can also be viewed as stand-alone research, because they interpret and explain gaps in the literature (Hong and Pluye, 2018; Snyder, 2019). The predominant type of reviews was descriptive by nature because there was a variation in how data were extracted and synthesized and encompassed the usage of science mapping tools as recommended by various researchers (Cooper *et al.*, 2018; Chen and Song, 2019). Building on the description provided by Xiao and Watson (2019), specific research topics were explored to give a historic and cross-sectional view of the literature. It is important to note that reviews may have flaws, and the researcher needs to perform some form of critical appraisal where the limitations of the review are explicitly stated (Hong and Pluye, 2018).

Prior research has revealed a gap in knowledge regarding the surveillance and monitoring of chemical contaminants, specifically the monitoring of essential and non-essential metals concerning routine surveillance. In addition, historical research studies did not address the efficiency of tools applied in monitoring heavy-metal contamination in food by EHPs. Lately, the trajectory of research encompasses several unexplored monitoring tools in public health. This includes the effectiveness and efficiency of ICP-OES and SEM-EDS for elemental analysis (Khalid *et al.*, 2018; Galagarza *et al.*, 2021). To fully understand how both techniques can be used in monitoring heavy metal contamination, their use and function in the field of Environmental Health should be further explored. Food contamination studies tend to be laboratory-based; seemingly, there is a practical knowledge gap in how EHPs can rapidly investigate and analyse samples collected in the field. There is a relatively adequate depth of research in spectrometry techniques in elemental analysis. In this study, the researcher seeks to establish new enquiry on methods for the detection and analysis of chemical contaminants in food. To date, there is minimal research on practical monitoring tools in chemical contamination studies. This is important and worthy of investigation within the context of Environmental Health.

This study encompassed an experimental design that involved the use of ICP-OES and SEM-EDS in the determination of heavy-metal accumulation in selected vegetables. The concentration levels were then compared to the South African standards for maximum allowable limits for heavy metals in food. The data were collected once-off, thus making the study employ a correctional time horizon.

2.4. Area description and sampling

The vegetable samples were collected in the Free State Province (29.0852° S, 26.1596° E). The specific location was the Mangaung Fresh Produce Market (29°06'52.6"S 26°15'41.8"E) as shown in Figure 2.2. It is the biggest fresh-produce farmer's market in Free State Province in South Africa. The vegetables sold at the market are from different farms across the Free State and are harvested under different conditions. In total, eighteen samples from six different types of vegetables of interest were collected according to their popularity within the area and analysed in triplicates.

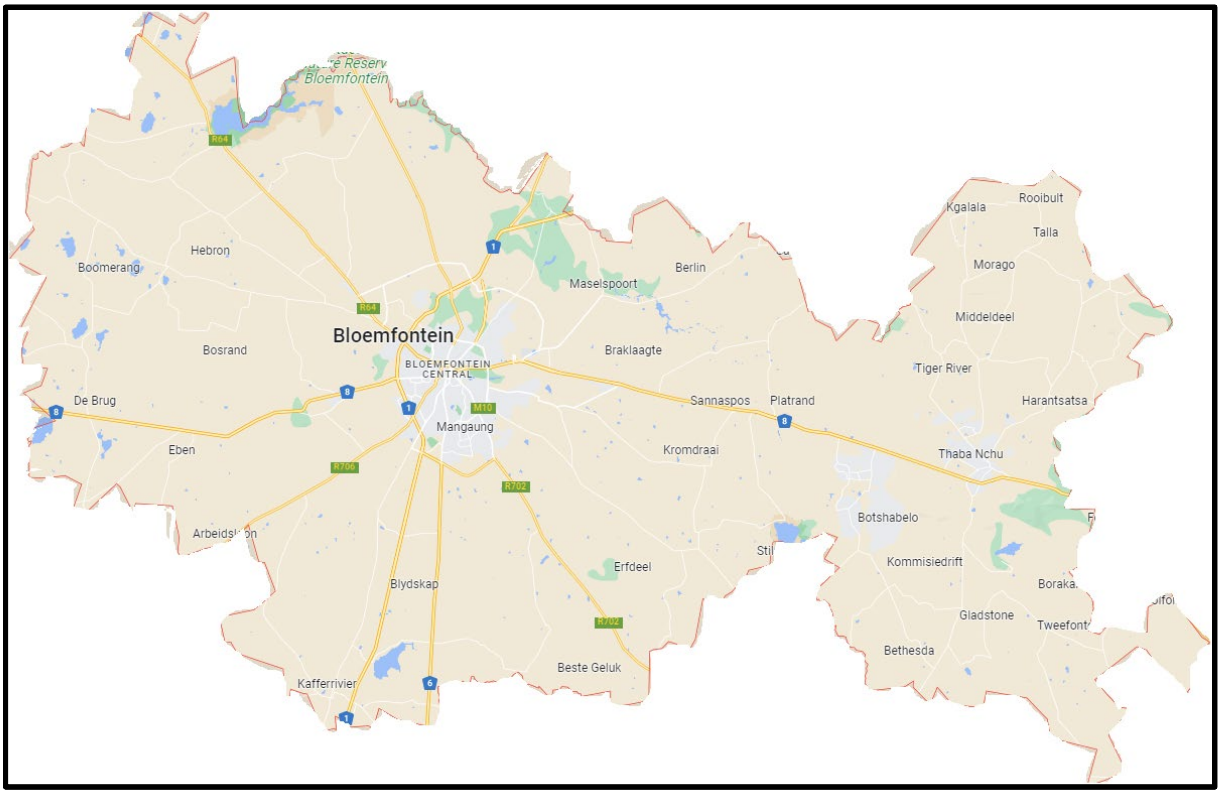


Figure 2.2: Mangaung Metropolitan Municipality, South Africa.

2.5. Investigation procedures and experiment preparation

2.5.1. The SEM-EDS technique

Scanning electron microscopy/energy dispersive X-ray spectrometry (SEM/EDS) is a widely used elemental microanalysis technique with the capability to identify and quantify all elements in the periodic table, excluding Hydrogen (H), Helium (He) and Lithium (Li) (Newbury and Ritchie, 2013). Moreover, it is can produce high-quality images at very high magnifications, better than the optical microscope (Chow *et al.*, 2020). A combination of the SEM-EDS and ICP-OES was noted as one of the efficient analytical tools for monitoring metals present in different matrices (Rezić, Špehar and Jakovljević, 2017; Scimeca *et al.*, 2018).

2.5.2. Energy dispersive X-ray spectroscopy (EDS) analysis

Dried and homogenised samples of 0.3 g of each vegetable type were placed on double-sided carbon discs mounted on aluminium stubs. To ensure the necessary X-ray conduction, the samples were coated with gold using the Leica EM ACE600 device (Wetzlar, Germany). The instrument parameters are reported in Table 2.1. The elemental composition of the sample was completed using the JEOL JSM-IT700HR (EN) California, United States of America) as shown in Figure 2.3.

The elemental concentration of heavy metals in the five vegetable types was analysed using the SEM-EDS. The corresponding peaks of the EDS measurement are depicted in Figure 2.4. Specific measurements revealed that Carbon (C), Oxygen (O) and Nitrogen (N) were abundant in all the vegetable samples. Both carbon and oxygen were chief components of all vegetable types because plants are known to naturally contain these elements. Both elements are found in organic residues and; thus easily distinguished on the analysed matter (Hayes *et al*., 2019). Carbon was measured in atomic %; beetroot (52.01%), spinach (55.22%), onion (58.11%), cabbage (55.35%) and tomato (52.04%). The only essential heavy metal detected was Copper (Cu), which is harmful in large quantities. The highest atomic percentage was found in beetroot and spinach (0.10%). This value is not significant enough to be considered a health risk. Reported health effects are abdominal disorders and other metabolic activity abnormalities.

The experiment showed that the electron beam can damage the sample by burning when high voltages were applied. Essentially, organic material reacted when the beam was focused over an extended period. Moreover, it was discovered that reducing the voltage affects the signal which assists with the reading of elemental data. Another factor that might have reduced the elemental data detected was that the samples had not been digested before the testing; thus there was no extraction of metals. However, improper extraction techniques and procedures can also affect the final output of the elemental data. The EDS measurements were not as sensitive as the ICP-OES results presented in Chapter 9. However, it could be that the selected sample particles for SEM-EDS analysis did not have the essential and non-essential elements.

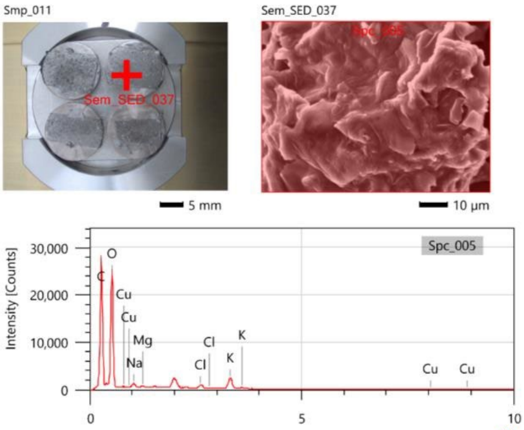
According to the findings of the experiment conducted, the SEM-EDS technique showed inefficiencies in detecting most essential and non-essential metals. As supported by Hayes *et* *al.* (2019), it can be used for initial screening. However, it can be more effective when integrated into a sequential protocol to analyse metals of choice.

Table 2.1: SEM-EDS Instrument conditions.

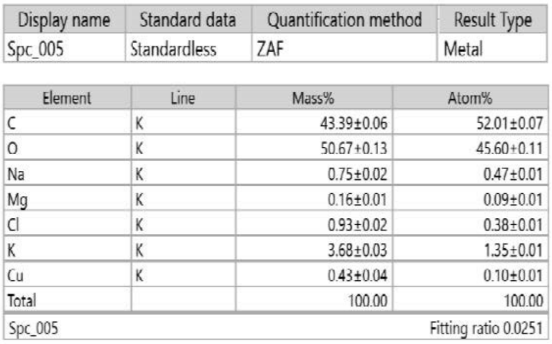
SEM-EDS	Electron source	Electron gun (with tungsten filament)
	Acceleration voltage (eV)	15.00
	Extraction beam apertures	energy-dispersive (EDS) detector
	Spot size	n/a
	Magnification	X100, X1600, X3000
	Detector	n/a
	Chamber pressure	n/a

Figure 2.3: Scanning Electron Microscopy equipment. Sample coating using the Leica EM ACE600 device (a). The elemental composition of the sample was completed using the JEOL JSM-IT700HR (EN). Receiver computer (c).

(A) Beetroot



(i)

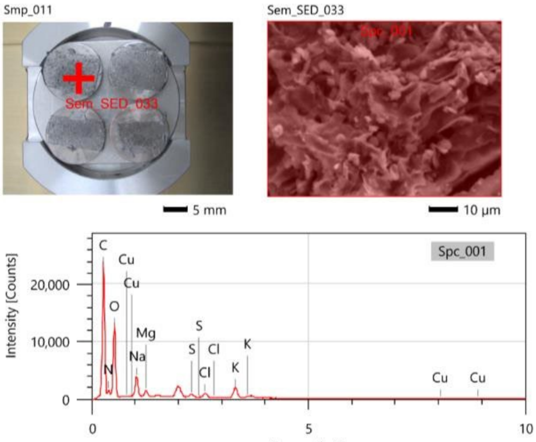


Display name	Standard data	Quantification method	Result Type
Spc_005	Standardless	ZAF	Metal

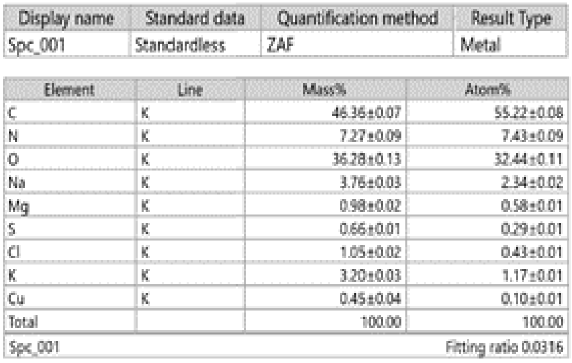
Element	Line	Mass%	Atom%
C	K	43.39±0.06	52.01±0.07
O	K	50.67+0.13	45.60+0.11
Na	K	0.75±0.02	0.47±0.01
Mg	K	0.16±0.01	0.09±0.01
Cl	K	0.93±0.02	0.38±0.01
K	K	3.68±0.03	1.35±0.01
Cu	K	0.43±0.04	0.10±0.01
Total		100.00	100.00
Spc_005			Fitting ratio 0.0251

(ii)

(B) Spinach



(iii)

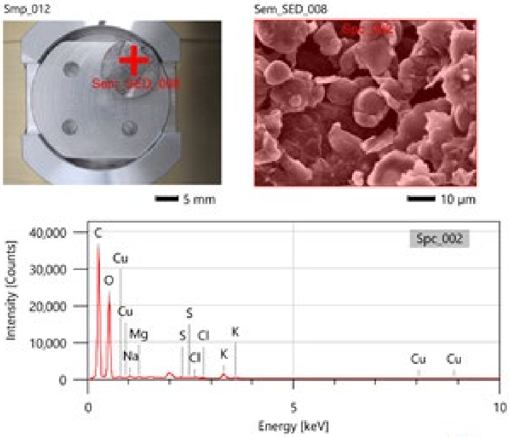


Display name	Standard data	Quantification method	Result Type
Spc_001	Standardless	ZAF	Metal

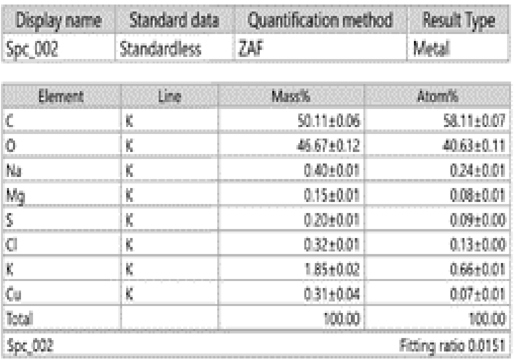
Element	Line	Mass%	Atom%
C	K	46.36±0.07	55.22±0.08
N	K	7.27±0.09	7.43±0.09
O	K	36.28±0.13	32.44±0.11
Na	K	3.76±0.03	2.34±0.02
Mg	K	0.98±0.02	0.58±0.01
S	K	0.66±0.01	0.29±0.01
Cl	K	1.05±0.02	0.43±0.01
K	K	3.20±0.03	1.17±0.01
Cu	K	0.45±0.04	0.10±0.01
Total		100.00	100.00
Spc_001			Fitting ratio 0.0316

(iv)

(C) Onion



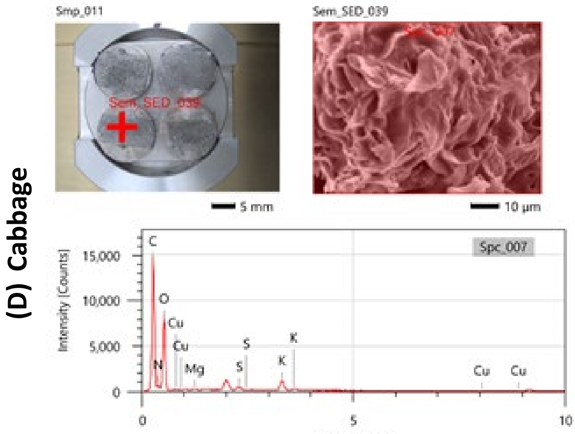
(V)



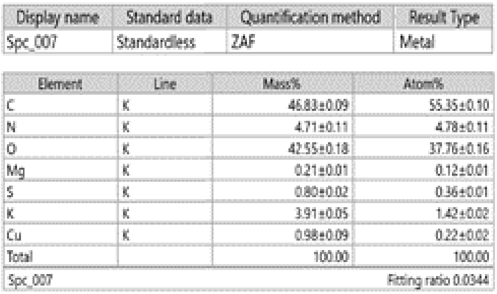
Display name	Standard data	Quantification method	Result Type
Spc_002	Standardless	ZAF	Metal

Element	Line	Mass%	Atom%
C	K	50.11±0.06	58.11±0.07
O	K	46.67±0.12	40.63±0.11
Na	K	0.40±0.01	0.24±0.01
Mg	K	0.15±0.01	0.08±0.01
S	K	0.20±0.01	0.09±0.00
Cl	K	0.32±0.01	0.13±0.00
K	K	1.85±0.02	0.66±0.01
Cu	K	0.31±0.04	0.07±0.01
Total		100.00	100.00
Spc_002			Fitting ratio 0.0151

(vi)



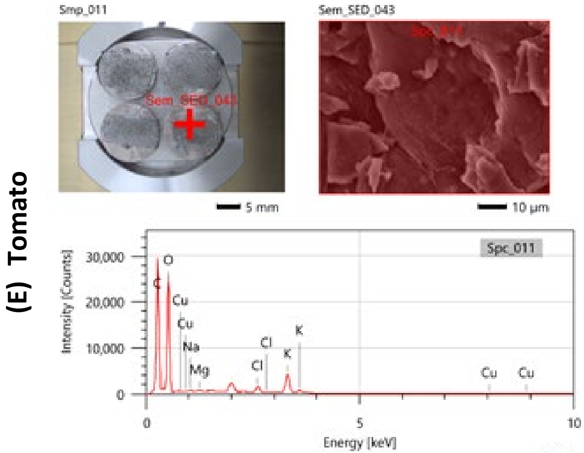
(vii)



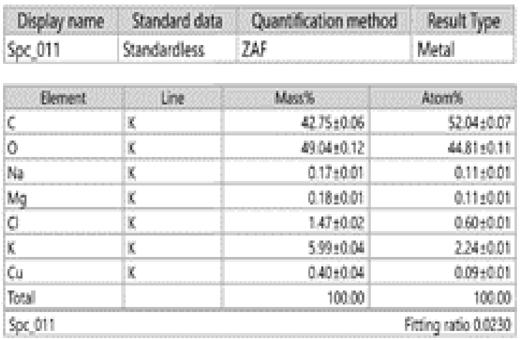
Display name	Standard data	Quantification method	Result Type
Spc_007	Standardless	ZAF	Metal

Element	Line	Mass%	Atom%
C	K	46.83±0.09	55.35±0.10
N	K	4.71±0.11	4.78±0.11
O	K	42.55±0.18	37.76±0.16
Mg	K	0.21±0.01	0.12±0.01
S	K	0.80±0.02	0.36±0.01
K	K	3.91±0.05	1.42±0.02
Cu	K	0.98±0.09	0.22±0.02
Total		100.00	100.00
Spc_007			Fitting ratio 0.0344

(viii)



(ix)



Display name	Standard data	Quantification method	Result Type
Spc_011	Standardless	ZAF	Metal

Element	Line	Mass%	Atom%
C	K	42.75±0.06	52.04±0.07
O	K	49.04±0.12	44.81±0.11
Na	K	0.17±0.01	0.11±0.01
Mg	K	0.18±0.01	0.11±0.01
Cl	K	1.47±0.02	0.60±0.01
K	K	5.99±0.04	2.24±0.01
Cu	K	0.40±0.04	0.09±0.01
Total		100.00	100.00
Spc_011			Fitting ratio 0.0230

(x)

Figure 2.4: EDS Spectrographs, weight ratio and morphology images at 10µm magnification. (A) Beetroot, (i) SEM and SEM-EDS (ii) elemental composition table. (B) Spinach, (iii) SEM and SEM-EDS (iv) elemental composition table. (C) Onion (v) SEM and SEM-EDS (vi) elemental composition table. (D) Onion, (vii) SEM and SEM-EDS (viii) elemental composition table. (A) Beetroot, (i) SEM and SEM-EDS (ii) elemental composition table. (E) Tomato, (ix) SEM and SEM-EDS (x) elemental composition table.

2.6. The ICP-OES technique

Spectroscopic techniques are widely applied and based on the generation and interpretation of atomic spectra. This spectrum is a result of contact of electromagnetic radiation with the analyte**.** Inductively coupled plasma optical emission spectroscopy (ICP-OES) is considered among the most accurate and sensitive techniques of instrumental analysis (Green *et al.*, 2003; Senila *et al.*, 2020; Planeta *et al.*, 2021; Khan *et al.*, 2022)**.** It is used due to its capability to identify multiple elements at the same time because of its linear range and high stability, low cost and efficiency, compared to other analytical techniques, such as the Inductively Coupled

Plasma Mass Spectrometry (ICP-MS), X-ray fluorescence, and Atomic Absorption Spectrometry (AAS) (Li *et al.*, 2021)**.** The key characteristic in the usage depends on the optimized parameters. Khan *et al.* (2022) state that a sample is normally injected into the ICP-OES instrument as a liquid sample towards a central channel of radiofrequency that is induced with argon plasma. Further, the solution is transformed in the form of a mist or aerosol through a nebulizer. Figures 2.5 and 2.6 show the typical system of the ICP-OES. It has been used to perform both qualitative and quantitative analyses of minerals. Moreover, this technique has been used widely in the determination of trace element contents in food samples (Bressy *et al.*, 2013; Fathabad *et al.*, 2018; Khan *et al.*, 2022).

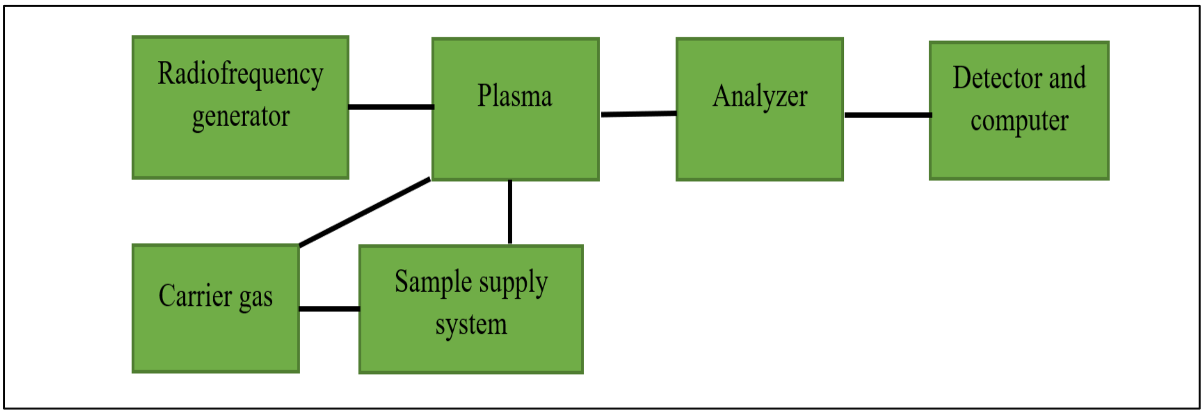


Figure 2.5: Illustration of the ICP-OES main components. A liquid sample is introduced towards a radiofrequency that is induced with argon plasma and then transformed in the form of a mist or aerosol through a nebulizer.

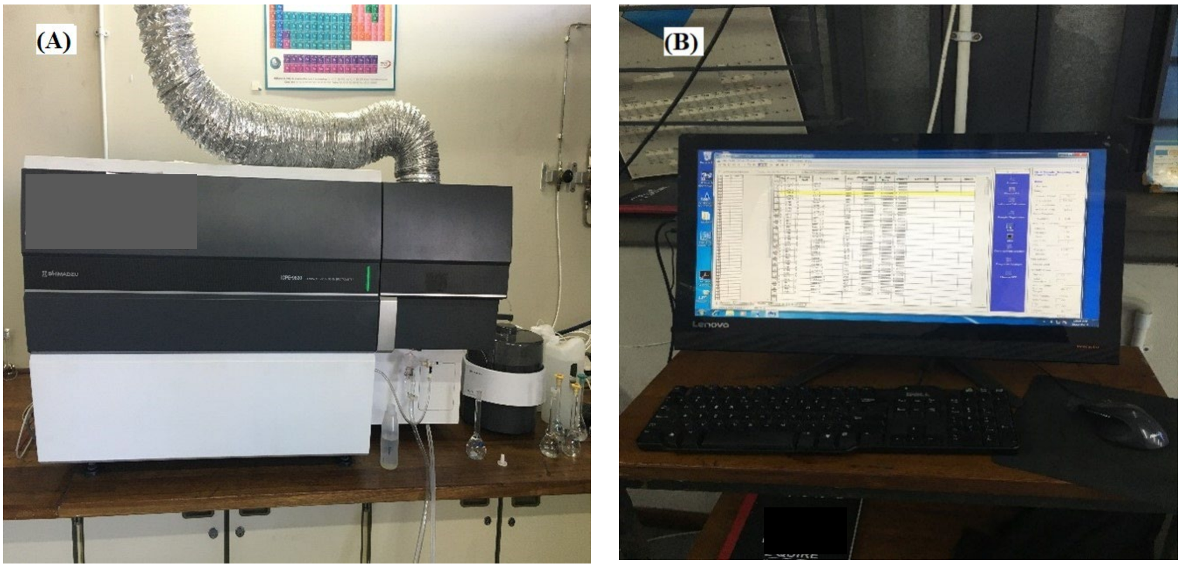


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Figure 2.6: (a) Plasma atomic emission spectrometer with a nebulizer and argon supply (Shimadzu, Model ICPE9820 made in Japan). (b) Computer and detector.

2.6.1. Material and methods – Inductively coupled plasma optical emission spectrometry

Food samples were purchased from the Mangaung Fresh Produce Market, stored in plastic Ziploc bags and brought to the laboratory within 2–3 hours of purchase. All samples were rinsed using distilled water and de-ionised water, then damped on a tissue to remove excess water and dried. The samples were peeled and then mashed using a titanium blade-blender to a smooth and homogenised product and then dried in an oven at a temperature of 60 °C for 48 hours. Dried vegetables were blended and sieved using a standard laboratory sieve of 150 microns. For each vegetable, samples were divided into triplicates. Measures were taken to minimise contamination using sterile hand gloves. The following genus species of the selected vegetables were purchased: cabbage (*Brassica oleracea*), carrot (*Daucus carota*), round tomato (*Solanum Lycopersicum*), spinach leaf (*Spinacia oleracea*), onion (*Allium*) and beetroot (*Beta vulgaris*). The heavy metals of interest in this study were: Arsenic (As), Cadmium (Cd), Lead (Pb), and Copper (Cu).

2.6.2. Final digestion procedure

Wet digestion methods for trace metal analysis consist of the chemical breakdown of sample matrices in a solution. This process involves the usage of chemicals to facilitate solubility (Twyman, 2000; Bizzi *et al.*, 2011). Open vessel acid digestion controlled for time and temperature was used to prepare the vegetable samples. This method has notable disadvantages, i.e. potential loss of trace elements, long digestion time, usage of bigger volumes of reagents and contamination (Hu and Qi, 2013). However, it ensures the completion of digestion. Previous studies (Ishak *et al.*, 2015) have noted that digestion methods should be measured according to the following variables: completeness of digestion, time taken to digest, the minimal or total advance of contamination, the safety of the procedure, and simplicity.

All labware was cleaned and soaked in nitric acid overnight and then thoroughly rinsed with deionized water during usage. A sample of 0.5 g dry mass weighed using an analytical balance was mixed with 10 ml of nitric acid 65% (HNO3) and 3 ml of hydrogen peroxide 35% (H2O2) in polypropylene centrifuge tubes (Nuapia, Chimuka and Cukrowska, 2018). These reagents are known to be effective in the digestion of biological samples and limit sample loss (Edokpayi *et al.*, 2022; Guo *et al.*, 2022; Sithole *et al.*, 2022; Torres *et al.*, 2022). The vessels were sealed and left to digest for 24 hours to obtain a clear solution. The samples were then heated on a hot plate for 15 minutes to complete the digestion process (Figures 2.7 and 2.8). However, careful consideration had to be made to guard against losing elements during heating or using large amounts of acid during digestion. Therefore, time had to be limited to avoid the loss of elements and evaporation of the solution. After heating, the digested sample solutions were cooled at room temperature and then brought to 50 ml volume with ultrapure, de-ionised water (Lion and Olowoyo, 2013). The solution was filtered using a Nalgene filtration system with throttle bottles and a 0.2-micron nitrate membrane filter. Then the filtrate was transferred to 50 ml polypropylene tubes washed with de-ionised water. The same method was applied for each prepared sample to prepare the blanks as the controls.

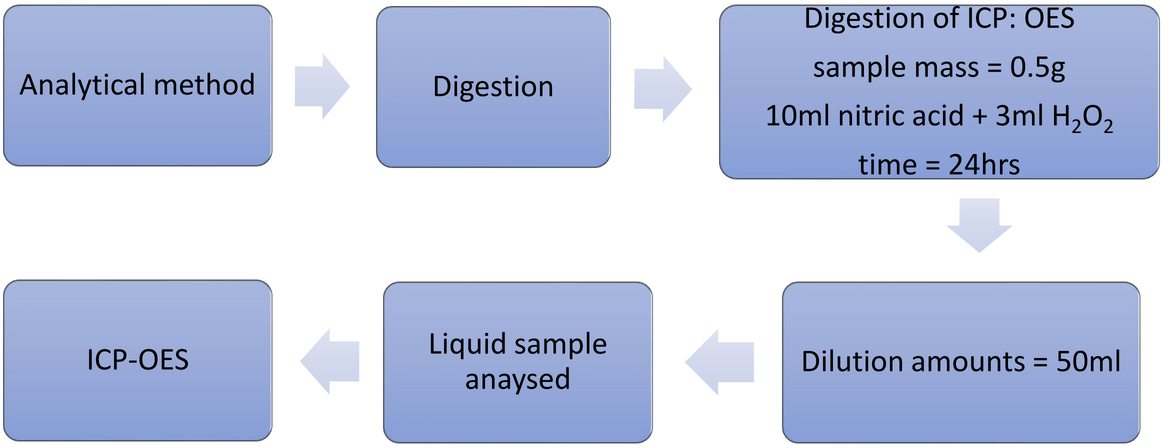

Figure 2.7: Illustration of the ICP-OES method for the analysis of vegetable samples (Digestion process to final solution).

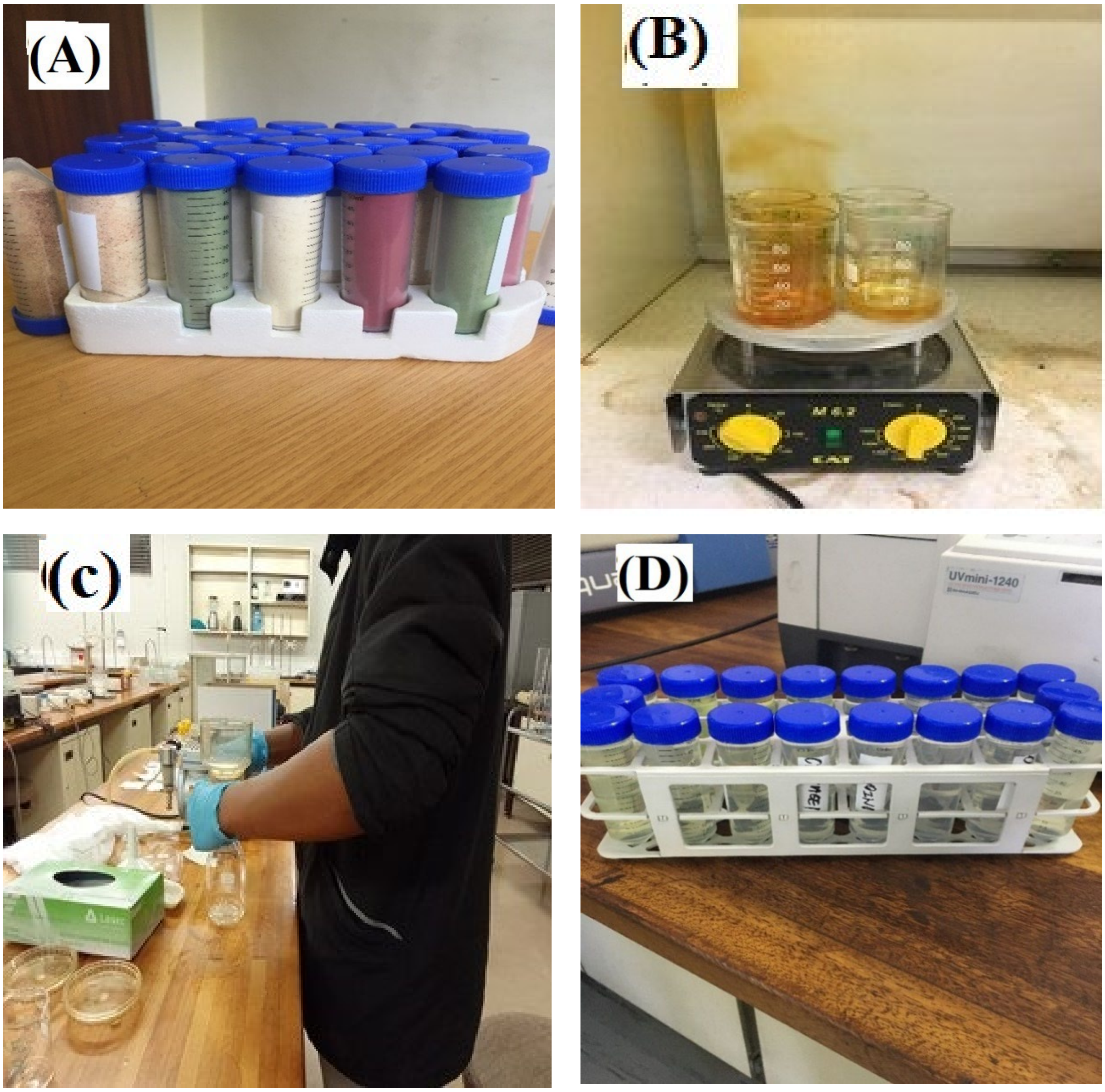

Figure 2.8: Ground vegetables and digested samples. Vegetables are ground into a fine powder (a). Nitrogen gas is released during heating and digestion (b). Filtration process (c). Clear solution ready for analysis (d).

2.7. Inclusion and exclusion criteria

The Mangaung Fresh Produce Market is the primary source of vegetables sold in the Metropolitan Municipality. Both formal and informal retailers (hawkers) get their products from the market. In this study, only vegetables sold directly at the market were considered. Other vegetables that are not considered a staple or popular choice of food were outside the scope of this study.

2.8. Data analysis

The data on the heavy metal concentration in the vegetables were coded by the researcher with the assistance of a professional statistician after data collection. The data were analysed on a Statistical Package for Social Sciences version 27 (SPSS). The first stage of the analysis involved data cleaning, editing, recording and checking for accuracy and inconsistencies. The second stage included a descriptive analysis of the data. Correlation analysis and one-way ANOVA were conducted to determine the relationship between the concentration levels of heavy metals in various vegetables. Further analysis included Spearman's rank correlation coefficient and cluster analysis to determine the significance of the differences and relationships between the metal contents of the vegetables. The specific analysis regarding health-risk assessments for non-carcinogenic and carcinogenic risk will include the calculation of target hazard quotient (THQ), total target hazard quotient (TTHQ), and chronic daily intake (CDI).

2.9 Study variables

The dependent variable in this study was the concentration of heavy metals in the vegetables, which was measured against the *Codex Alimentarius* standards/allowable limit for trace elements and independent variables such as populations at risk and the efficiency of the ICP-OES and SEM-EDS technique as a monitoring and surveillance tools.

2.10. Ethical considerations statement

This study was approved by the Central University of Technology Faculty Research Committee. In this study, no specific farm names were revealed concerning the purchased samples. The research findings do not implicate any farm and the data are generalised in the thesis and subsequent publications to be submitted to the Central University of Technology, Free State.

2.11. References

Azevedo, L. F. *et al.* (2011) 'Como escrever um artigo científico – estruturação e redacção da secção de métodos', *Revista Portuguesa de Pneumologia*, 17(5), pp. 232–238. doi: 10.1016/j.rppneu.2011.06.014.

Bizzi, C. A. *et al.* (2011) ‘Understanding the process of microwave-assisted digestion combining diluted nitric acid and oxygen as auxiliary reagent’, *Microchemical Journal*, 99(2), pp. 193–196. doi: 10.1016/j.microc.2011.05.002.

Bressy, F. C. *et al.* (2013) ‘Determination of trace element concentrations in tomato samples at different stages of maturation by ICP-OES and ICP-MS following microwave-assisted digestion’, *Microchemical Journal*, 109, pp. 145–149. doi: 10.1016/j.microc.2012.03.010.

Chen, C. C. and Song, M. (2019) ‘Visualizing a field of research : A methodology of systematic scientometric reviews’, *PLoS ONE*, 14(10). doi: 10.1371/journal.pone.0223994.

Chow, F. W. *et al.* (2020) ‘A Rapid, Simple, Inexpensive, and Mobile Colorimetric Assay COVID-19-LAMP for Mass On-Site Screening of COVID-19’, 19.

Cooper, C. *et al.* (2018) ‘Defining the process to literature searching in systematic reviews : a literature review of guidance and supporting studies’, pp. 1–14.

Cresswell, J. (2016) *Research Design: Qualitative, Quantitative, and Mixed methods Approaches*. 4th ed. California: SAGE Publications Inc.

Edokpayi, J. N. *et al.* (2022) ‘Water quality assessment and potential ecological risk of trace metals in sediments of some selected rivers in Vhembe district , South Africa’, *Physics and Chemistry of the Earth*, (January), p. 103111. doi: 10.1016/j.pce.2022.103111.

Fathabad, A. E. *et al.* (2018) ‘Determination of heavy metal content of processed fruit products from Tehran’s market using ICP-OES: A risk assessment study’, *Food and Chemical Toxicology*, 115(April), pp. 436–446. doi: 10.1016/j.fct.2018.03.044.

Ferreira, S. L. C. *et al.* (2017) ‘Robustness evaluation in analytical methods optimized using experimental designs’, *Microchemical Journal*, 131, pp. 163–169. doi: 10.1016/j.microc.2016.12.004.

Galagarza, O. A. *et al.* (2021) ‘Occurrence of Chemical Contaminants in Peruvian Produce : A Food-Safety Perspective’, pp. 1–21.

Green, D. R. H. *et al.* (2003) ‘Optimization of an inductively coupled plasma-optical emission spectrometry method for the rapid determination of high-precision Mg/Ca and Sr/Ca in foraminiferal calcite’, *Geochemistry, Geophysics, Geosystems*, 4(6), pp. 1–11. doi: 10.1029/2002GC000488.

Guo, J. *et al.* (2022) ‘Incorporating in vitro bio-accessibility into human health risk assessment of heavy metals and metalloid (As) in soil and pak choi (Brassica chinensis L .) from greenhouse vegetable production fields in a megacity in Northwest China’, *Food Chemistry*, 373(PB), p. 131488. doi: 10.1016/j.foodchem.2021.131488.

Hayes, E., Cnuts, D. and Rots, V. (2019) ‘Integrating SEM-EDS in a sequential residue analysis protocol: Benefits and challenges’, *Journal of Archaeological Science: Reports*, 23(November 2018), pp. 116–126. doi: 10.1016/j.jasrep.2018.10.029.

Hong, Q. and Pluye, P. (2018) ‘for Critical Appraisal in Systematic Mixed Studies Reviews’, *Journal of Mixed Methods Research*, pp. 1–15. doi: 10.1177/1558689818770058.

Hu, Z. and Qi, L. (2013) ‘Sample Digestion Methods’, *Treatise on Geochemistry: Second Edition*, 15(November), pp. 87–109. doi: 10.1016/B978-0-08-095975-7.01406-6.

Ishak, I. *et al.* (2015) ‘Comparison of digestion methods for the determination of trace elements and heavy metals in human hair and nails’, *Malaysian Journal of Medical Sciences*, 22(6), pp. 11–20.

Jackson, S. L. (2009) *Research Methods and Statistics: A Critical Thinking Approach*. 3rd ed. Available at: www.ichapters.com.

Johnson, Burke; Christensen, L. (2014) *Educational Research: Quantitative, Qualitative, and Mixed methods Approaches*. 5th ed. California: SAGE Publications Inc.

Khaldi, K. (2017) ‘Quantitative, Qualitative or Mixed Research: Which Research Paradigm to Use?’, *Journal of Educational and Social Research*, 7(2), pp. 15–24. doi: 10.5901/jesr.2017.v7n2p15.

Khalid, S. *et al.* (2018) ‘A review of environmental contamination and health risk assessment of wastewater use for crop irrigation with a focus on low and high-income countries’, *International Journal of Environmental Research and Public Health*, 15(5), pp. 1–36. doi: 10.3390/ijerph15050895.

Khan, S. R. *et al.* (2022) 'Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES): a Powerful Analytical Technique for Elemental Analysis', *Food Analytical Methods*, 15(3), pp. 666–688. doi: 10.1007/s12161-021-02148-4.

Kim, Y. and Steiner, P. (2016) 'Quasi-Experimental Designs for Causal Inference', *Educational Psychologist*, 51(3–4), pp. 395–405. doi: 10.1080/00461520.2016.1207177.

Leatherdale, S. T. (2019) 'Natural experiment methodology for research : a review of how different methods can support real-world research different methods can support real-world research', *International Journal of Social Research Methodology*, 22(1), pp. 19–35. doi: 10.1080/13645579.2018.1488449.

Li, X. *et al.* (2021) 'Optimization of ICP-OES's parameters for uranium analysis of rock samples', *Journal of the Korean Physical Society*, 78(9), pp. 737–742. doi: 10.1007/s40042-021-00093-3.

Lion, G. N. and Olowoyo, J. O. (2013) 'Population health risk due to dietary intake of toxic heavy metals from Spinacia oleracea harvested from soils collected in and around Tshwane, South Africa', *South African Journal of Botany*, 88, pp. 178–182. doi: 10.1016/j.sajb.2013.07.014.

Marczyk, G., DeMatteo, D. and Festinger, D. (2005) *Essentials of Research Design and Methodology*. Edited by N. L. Kaufman and A. S. Kaufman. New Jersey: John Wiley & Sons, Inc.

Newbury, D. E. and Ritchie, N. W. M. (2013) 'Is scanning electron microscopy/energy dispersive X-ray spectrometry (SEM/EDS) quantitative?', *Scanning*, 35(3), pp. 141–168. doi: 10.1002/sca.21041.

Nuapia, Y., Chimuka, L. and Cukrowska, E. (2018) 'Assessment of heavy metals in raw food samples from open markets in two African cities', *Chemosphere*, 196, pp. 339–346. doi: 10.1016/j.chemosphere.2017.12.134.

Planeta, K. *et al.* (2021) *The assessment of the usability of selected instrumental techniques for the elemental analysis of biomedical samples*, *Scientific Reports*. Nature Publishing Group UK. doi: 10.1038/s41598-021-82179-3.

Rezić, I., Špehar, M. and Jakovljević, S. (2017) ‘Characterization of Ag and Au nanolayers on Cu alloys by TLC, SEM-EDS, and ICP-OES’, *Materials and Corrosion*, 68(5), pp. 560–565. doi: 10.1002/maco.201609176.

Scimeca, M. *et al.* (2018) ‘Energy dispersive X-ray (EDX) microanalysis: A powerful tool in biomedical research and diagnosis’, *European Journal of Histochemistry*, 62(1), pp. 89–99. doi: 10.4081/ejh.2018.2841.

Senila, M. *et al.* (2020) ‘Performance parameters of inductively coupled plasma optical emission spectrometry and graphite furnace atomic absorption spectrometry techniques for pd and pt determination in automotive catalysts’, *Materials*, 13(22), pp. 1–13. doi: 10.3390/ma13225136.

Sithole, S. C. *et al.* (2022) ‘Journal of King Saud University – Science Elemental concentration of heavy metals in oyster mushrooms grown on mine polluted soils in Pretoria , South Africa’, *Journal of King Saud University - Science*, 34(2), p. 101763. doi: 10.1016/j.jksus.2021.101763.

Snyder, H. (2019) ‘Literature review as a research methodology : An overview and guidelines’, *Journal of Business Research*, 104 (August), pp. 333–339. doi: 10.1016/j.jbusres.2019.07.039.

Torres, L. G. *et al.* (2022) ‘Talanta Open Development of validation methods to determine cadmium in cocoa almond from the beans by ICP-MS and ICP-OES’, 5. doi: 10.1016/j.talo.2021.100078.

Twyman, R. M. (2000) ‘The Nature of the Sample Matrix Extraction of the Analyte’, *Analysis*, pp. 184–191.

Xiao, Y. and Watson, M. (2019) ‘Guidance on Conducting a Systematic Literature Review’. doi: 10.1177/0739456X17723971.

CHAPTER 3:

THE SURVEILLANCE AND PREDICTION OF FOOD CONTAMINATION USING INTELLIGENT SYSTEMS: A BIBLIOMETRIC ANALYSIS

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Abstract

In this paper, we report the bibliometric research trends on the application of machine learning/intelligent systems in the prediction of food contamination and the surveillance of foodborne diseases. The Web of Science (WoS) core collection database was used to retrieve publications from 1996–2021. Documents were classified according to country of origin, journal citations, and key research areas. The bibliometric parameters were analysed using VOSviewer version 1.6.15 to visualize the international collaboration networks, citation density, and link strength. A total of 516 articles across six different types of documents were extracted, with an average *h*-index of 51 from 10 570 citations. The leading journal in publications was *Science of the Total Environment* (3.6%) by Elsevier and the *International Journal of Food Microbiology* (2.5%). The USA (24%), followed by the People's Republic of China (17.2%), were the two most influential countries in publications. The top-cited articles in this study focus on themes such as contamination from packaging materials and the strategies for preventing chemical contaminants in the food chain. Early detection and forecasting systems for foodborne disease outbreaks can assist public health professionals to respond efficiently, given that relevant data are transmitted timeously. This report is significant because the public health field requires innovative strategies in forecasting foodborne disease outbreaks to advance effective interventions. Therefore, more collaborations need to be fostered, especially in developing nations regarding food safety research.

Keywords: Bibliometric analysis; food contamination; machine learning; foodborne diseases; VOSviewer

3.1. Introduction

The The World Health Organization (WHO) defines foodborne diseases as illnesses resulting from the ingestion of contaminated foodstuffs; the contamination can be from the environmental pollution in water, soil, and air caused by chemicals and microorganisms (Abdul Rasam and Mohd Noor, 2012). Foodborne outbreaks have been occurring for centuries and have continued to torment health authorities. Therefore, in addition to medical examination of the affected individuals, most researchers recommend the implementation of training programmes in food safety to form a more comprehensive food control system (Manes, Liu and Dworkin, 2013; Basavegowda *et al.*, 2014; Djekic *et al.*, 2014; Gumbo *et al.*, 2015). Forecasting foodborne disease outbreaks is a public health strategy that is multifaceted, with socio-economic benefits. In recent years, technologies have been used to investigate foodborne outbreaks. Reconstruction networks can be used to analyse the causes of foodborne outbreaks through 'trace back and trace forward' of food items suspected to be problematic in the food supply chain (Weiser *et al.*, 2016). Machine learning and intelligent systems and statistical inferences such as the Bayesian approach to real-time monitoring and prediction can be useful techniques to monitor foodborne diseases. Lately, 'nowcasting' is used as an effective tool in the surveillance of current events and the prediction of foodborne epidemics (Benke and Benke, 2018; Wang *et al.*, 2018; Yang, Zhang and Ma, 2020; Ben Ayed and Hanana, 2021). The combination of the two methods was reported to assist in the early warning and detection of outbreaks.

The food industry in general is susceptible to the negative effects of foodborne diseases (Bennett *et al.*, 2015). Thus, the inception of stringent measures through food laws internationally and regionally is considered due to the devastating impact of foodborne diseases. The trade industry has seen a rise in food imports and exports due to global demand. International bodies and governments have come up with systems to curb the influence of disease along the food supply chain, but the receivers at the consumer level are the most affected because of factors beyond their control (Havelaar *et al.*, 2015; Magalhães *et al.*, 2019; Nosratabadi *et al.*, 2021). Indeed, food hygiene practices can be largely to blame, but in some cases, climatic conditions are the determining factor between health and sickness caused by the unwholesomeness of the food (Na *et al.*, 2016). Countries that are not food secure are affected negatively by emerging foodborne illnesses, which can be attributed to a lack of infrastructure, whether sanitation or agriculture-related. The following have been reported as the main foodborne illnesses across the reviewed literature: norovirus infection, also known as viral gastroenteritis (Havelaar *et al.*, 2015), Listeriosis caused by *Listeria monocytogenes* (Ebel *et al.*, 2016), Salmonellosis, Campylobacteriosis, *Escherichia coli* O157:H7 infection (Gould *et al.*, 2013; Ebel *et al.*, 2016; Sweileh *et al.*, 2016), Shigellosis, and Vibrio infection – *Vibrio parahaemolyticus* (Na *et al.*, 2016; Osei-Tutu and Anto, 2016). There are other causes of illness as a result of chemical hazards in the form of heavy metals and pesticide exposure contaminating food sources (Geueke, Groh and Muncke, 2018; Mehdi *et al.*, 2018; Antoniadis *et al.*, 2019; Ernstoff *et al.*, 2019; Feng *et al.*, 2021).

Public health authorities are in constant need to collect, analyse and disseminate information to relevant sectors (Ford *et al.*, 2015; Amene *et al.*, 2016; Osei-Tutu and Anto, 2016; Shonhiwa *et al.*, 2019; Tchatchouang *et al.*, 2020). Similarly, in foodborne disease surveillance, vital information needs to be used to assess the incidence and prevalence of specific pathogens causing illnesses (Lee, 2017). Furthermore, taking into consideration the high mortality rate reported by the World Health Organization i.e. 430 000 deaths, the importance of surveillance activities in food control cannot be overestimated (Lee, 2017). A tiered approach with elements of all three types is recommended since no single approach can offer all the required information. This will need to be supplemented by big-data mining and synthesis for effective evidence-based decision-making. These systems will require human-resource capacity and complex digital systems to handle the immense volumes of data (Lee, 2017; Zhou *et al.*, 2019; Adisa *et al.*, 2020). This lack of capacity is a reality in developing countries where systems are usually not in place and the resources are limited (Mayet *et al.*, 2011; Gould *et al.*, 2013; Shonhiwa *et al.*, 2019).

Economies in many nations have been destabilized at some point due to foodborne illnesses. This usually happens by affecting the food supply and the public health system by overwhelming the already limited resources (Käferstein, 2003; Havelaar *et al.*, 2015; Lake, 2017). In the United States of America, $15.5 billion was estimated to be the annual burden on the economy resulting from foodborne illness (Hoffmann *et al.*, 2015). The burden of the illnesses was calculated based on medical costs and loss of productivity as indices. The 2017–2018 *Listeria monocytogenes* outbreak in South Africa has proven the devastating impact of an outbreak on the economy. Consequently, markets were affected negatively and food safety policies were questioned by international organizations (Tchatchouang *et al.*, 2020). Firstly, the cost of hospitalization, which included the recovery period of the patients, was R1,5 billion (US $ 10.4 million). Secondly, the loss of productivity and export of products was R2,19 billion (US $15 million). Lastly, the economic loss due to crashing shares on trade platforms and other indices was R3,79 billion (US $260 million).

Bibliometrics is considered a cross-disciplinary science that encompasses the usage of statistical methods in the analysis of knowledge databases (Liao *et al.*, 2018; Dhital and Rupakheti, 2019; Zyoud, 2019; Secinaro and Calandra, 2021). Essentially, it is a part of science devoted to the identification of the trends of a particular field of study (Latino, Menegoli and Corallo, 2020; Vila-Lopez and Küster-Boluda, 2020). Bibliometric analysis is widely used in various disciplines. In public health, it can be used to study the research trends and ascertain the influential organizations and countries in particular fields of research (Dos Santos *et al.*, 2019; Meng *et al.*, 2020; Sweileh and Moh'd Mansour, 2020; Yu *et al.*, 2020). Thus, the intensity of research in each field can be determined and further improved.

3.2. Data sources and methods

Researchers considered different approaches to data collection in this study. Literature shows that there is a debate between the use of Scopus and Web of Science (WoS) regarding superiority (Secinaro and Calandra, 2021). Other researchers assert that both indices can introduce bias due to heavily cited fields such as biomedical research and the natural sciences and engineering (Mongeon and Paul-Hus, 2016). Moreover, other researchers (Zhu and Liu, 2020) believe there is no concrete evidence on which index is better. In this study, WoS was used as a sole database to ensure consistency, and avoid duplication and overlap in data collection (Obileke *et al.*, 2020). In addition, WoS is widely used by global researchers in a variety of knowledge domains (Li, Rollins and Yan, 2018).

The literature data on the surveillance and prediction of food contamination using intelligent systems published between 1996–2021 were retrieved topically, using the WoS core collection database. The citation indexes used in this study are the Science Citation Index Expanded (SCI-EXPANDED), Social Sciences Citation Index (SSCI), Arts & Humanities Citation Index (A&HCI), Conference Proceedings Citation Index Sciences (CPCI-S), Conference

Proceedings Citation Index Social Sciences & Humanities (CPCI-SSH), Book Citation Index Sciences (BKCI-S), Book Citation Index Social Sciences & Humanities (BKCI-SSH), and Emerging Sources Citation Index (ESCI) due to their robust scientific authority and frequent use in bibliometric analysis by various researchers (Yi, Yang and Sheng, 2016; Yu and Liao, 2016; Liu and Liao, 2017; Liao *et al.*, 2018). The closest matching search terms selected to identify publications by topic were 'Food contamination' and 'Prediction' or 'Artificial intelligence', 'Machine learning, or 'Artificial neural network', as shown in Figure 3.1. Furthermore, full records, which include abstracts, cited references, sources and authors were exported to 'Tab-delimited' file format for windows. During the process of retrieval, language was not considered a limitation. Further information regarding publications included the document type, author affiliation, year of publication and journal name. The information was retrieved on the 15th of January 2021 and was further processed using VOSviewer version 1.6.15 software for mapping and visualization purposes (Van Eck and Waltman, 2010). This software was used to analyse the co-citation, co-authorship, co-occurrence and bibliographic coupling of documents (Meng *et al.*, 2020; Secinaro and Calandra, 2021). The analysis was presented as a network, overlay map and density visual.

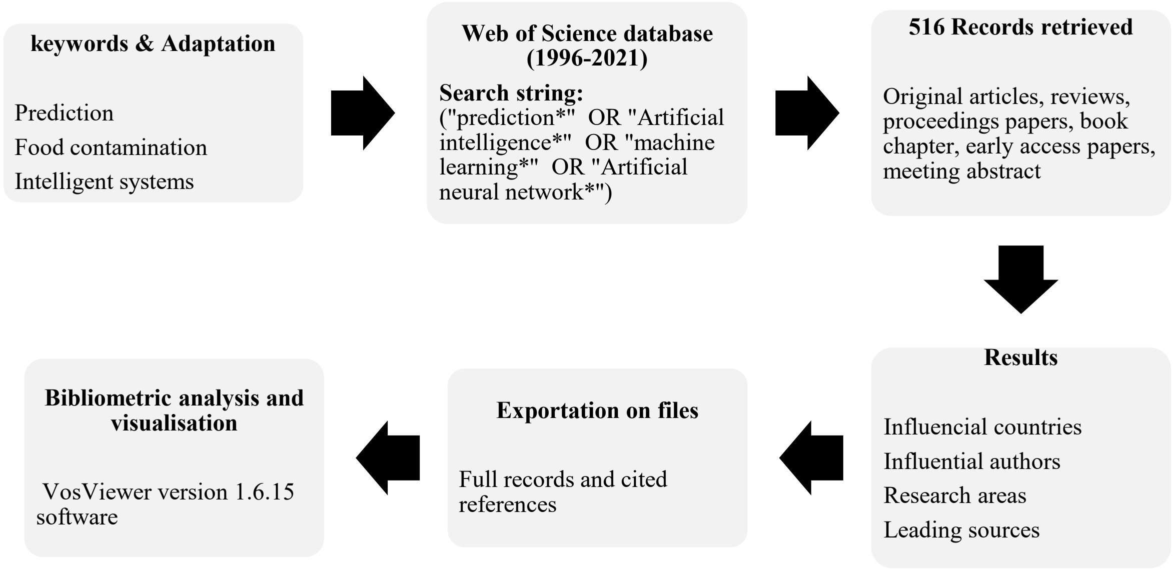

Figure 3.1: Search flow methodology.

3.3. Findings

In this study, 516 papers met the selection criteria. The document type that appears the most is the article (450), accounting for 87.2% of the total number of publications as shown in Table 3.1. The second-most frequent document type was review papers (43), with a total percentage of 8.3%. In the third position is conference proceedings papers (36), with a proportion of 6.9%. Further results in this study show that book chapters (6), early-access papers (2) and meeting abstracts (1) accounted for less proportion in the ranking of publications. Table 3.1 below shows the ranking of document types.

Table 3.1: Type of document.

Ranking	Type of document	Frequency	% N = 516
1	Articles	450	87.20
2	Review	43	8.33
3	Proceeding's paper	36	6.97
4	Book chapter	6	1.16
5	Early access	2	0.38
6	Meeting abstract	1	0.19

Table 3.2 shows the top 10 research areas during the bibliometric analysis. The analysis shows that research on food contamination and machine learning predominantly revolves around the following main themes: food science and technology (32.3%), environmental sciences ecology (26.9%), chemistry (11.6%) and agriculture (10.6%).

Table 3.2: List of top 10 research areas of publication

Ranking	Research area	Frequency	% N = 516
1	Food science and technology	167	32.36
2	Environmental Sciences Ecology	139	26.93
3	Chemistry	60	11.62
4	Agriculture	55	10.65
5	Biotechnology applied microbiology	51	9.88
6	Toxicology	50	9.69
7	Microbiology	49	9.49
8	Engineering	44	8.52
9	Public Environmental Occupational Health	25	4.84
10	Computer science	18	3.48

Figure 3.2 shows the trend of publications related to food contamination and machine learning from 1997 to 2021. The results reveal that in the first 15 years (1997–2012), the growth was gradual, indicating a steady, but slow growth rate. However, a sharp spike is observed from 2013 to 2020. Prominently, the years 2019 (67) and 2020 (66) netted the highest number of research publications. A further 44 and 35 publications were reported in the year 2018 and 2017, respectively. The overall results show that the degree of research intensity is increasing in this field. It is important to note that the observed decline in publication numbers after the year 2020 is possibly due to the study period which ended in mid-January, which could have excluded publications yet to be indexed.

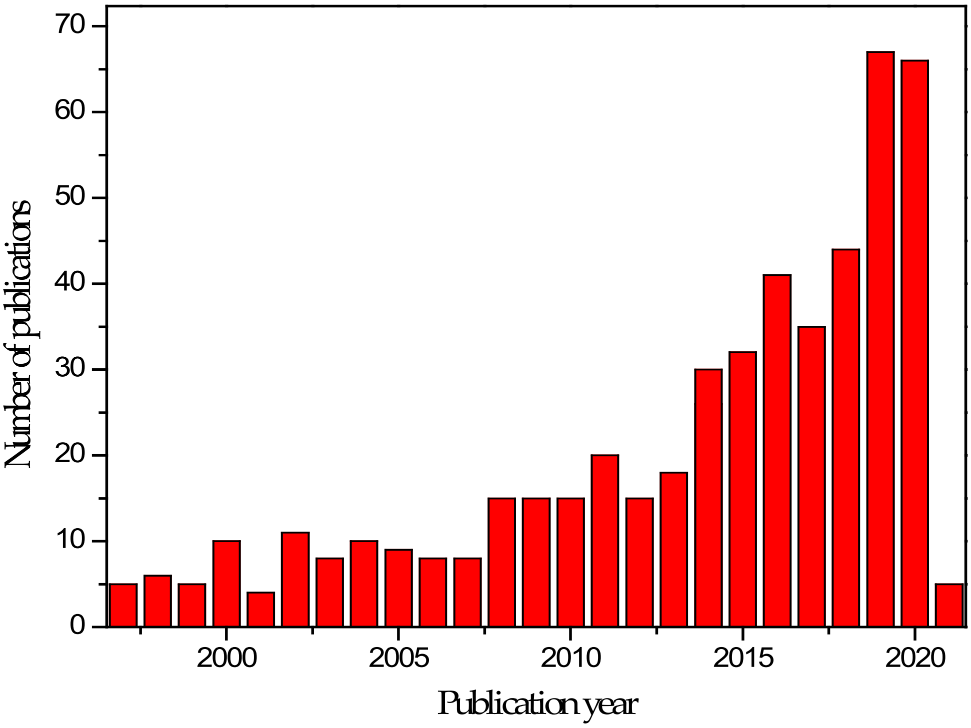

Figure 3.2: The annual trends of food contamination-related publications (1997-2021).

The results from the study show that some journals are more productive in comparison with others. In the first position, the *Science of the Total Environment Journal* was the biggest contributor with 19 publications. *International Journal of Food Microbiology* and *Journal of Food Protection* came in second and third, respectively with 13 publications. *Food Control* came in fourth (12), with *Environmental Science Technology* (11), coming in at the fifth position. Table 3 below shows the top 10 sources that published the most papers.

Table 3.3: Top 10 most productive (active) journals in publishing food contamination research.

Ranking	Productive sources	Frequency	% N = 516
1	*Science of the Total Environment*	19	3.68
2	*International Journal of Food Microbiology*	13	2.51
3	*Journal of Food Protection*	13	2.51
4	*Food Control*	12	2.32
5	*Environmental Science Technology*	11	2.13
6	*Food additives & contaminants. Part A, Chemistry, analysis, control, exposure & risk assessment*	11	2.13
7	*Food Microbiology*	10	1.93
8	*Environmental Toxicology and Chemistry*	9	1.74
9	*Environmental Science and Pollution Research*	8	1.55
10	*Journal of Environmental Radioactivity*	8	1.55

The United States of America ranks first, with the highest number of research outputs (24.03%) in the top 10 countries with the highest research publications. The People's Republic of China ranks second regarding the number of publications (17.24%), while there is a significant gap up to third-ranked England (7.94%). Table 3.4 shows the top 10 most productive countries in food contamination studies.

Table 3.4: Top 10 number of publications per country.

Ranking	Influential countries	Frequency	% N = 516
1	United States of America	124	24.03
2	People's Republic of China	89	17.24
3	England	41	7.94
4	France	38	7.36
5	Italy	34	6.58
6	Germany	33	6.39
7	Netherlands	31	6.0
8	Spain	27	5.23
9	Canada	24	4.65
10	Switzerland	18	3.48

The co-authorship analysis is shown in Figure 3.3. The multicolours in the network illustrate the different directions in the trajectory of research. There are seven clusters in the network, with the biggest clusters having four items. The distance and the thickness of the links in the red cluster (Ding Changfeng; Li Xingxiang; Wang Xingxiang and Zhang Taolin) show a strong level of cooperation between the authors' collaborative efforts, compared to the cluster in green (Panagou Efstathios and Tsanikas Panagiotis). Authors such as Sun Da-Wen have weak links with the rest of the authors, due to a lack of co-authorship initiatives. Figure 3.4 shows the density visualization of the cluster of collaborative authors. The more concentrated colours depict the increase in research outputs.

Figure 3.3: Co-authorship by author unit analysis.

Figure 3.4: Co-authorship by author unit analysis (density visualization).

Figure 3.5 represents the analysis of co-authorship by country. Eight (8) clusters were assigned by the programme, whereby three of the biggest clusters in the network had five items each. The cluster with the strongest link of international co-author collaborations includes the USA, Ireland, China and Turkey. The network also shows that Turkey is secluded from the USA, which is a sign of weak collaborations, depicted by a thin line and the distance. The overlay visualizations in Figure 3.6 shows that the most recent collaboration was in 2016 between China, Iran, Greece and India.

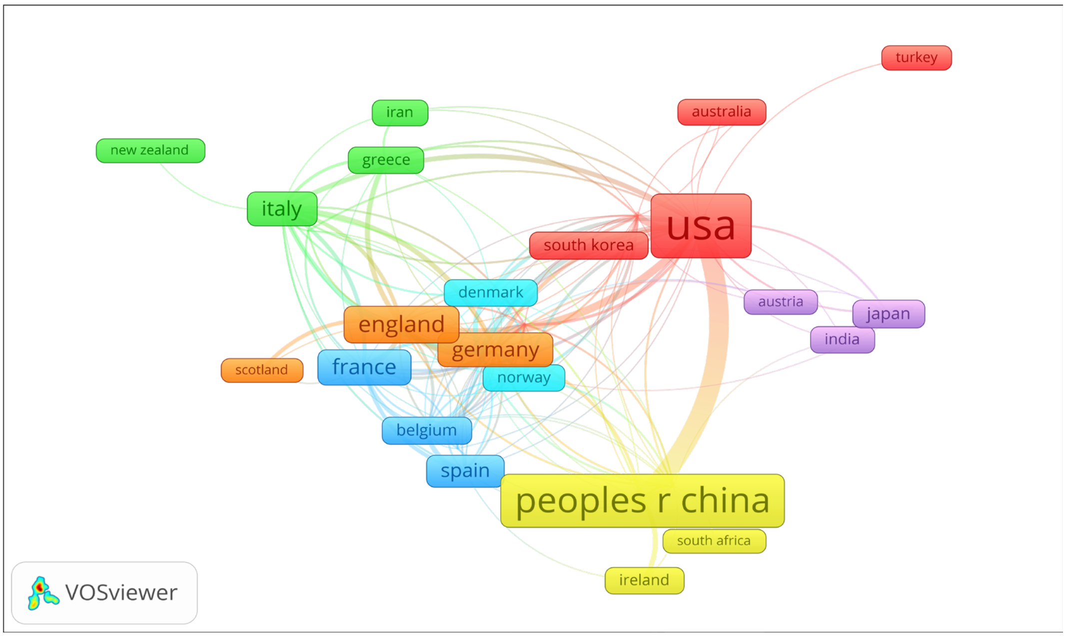

Figure 3.5: Co-author by countries.

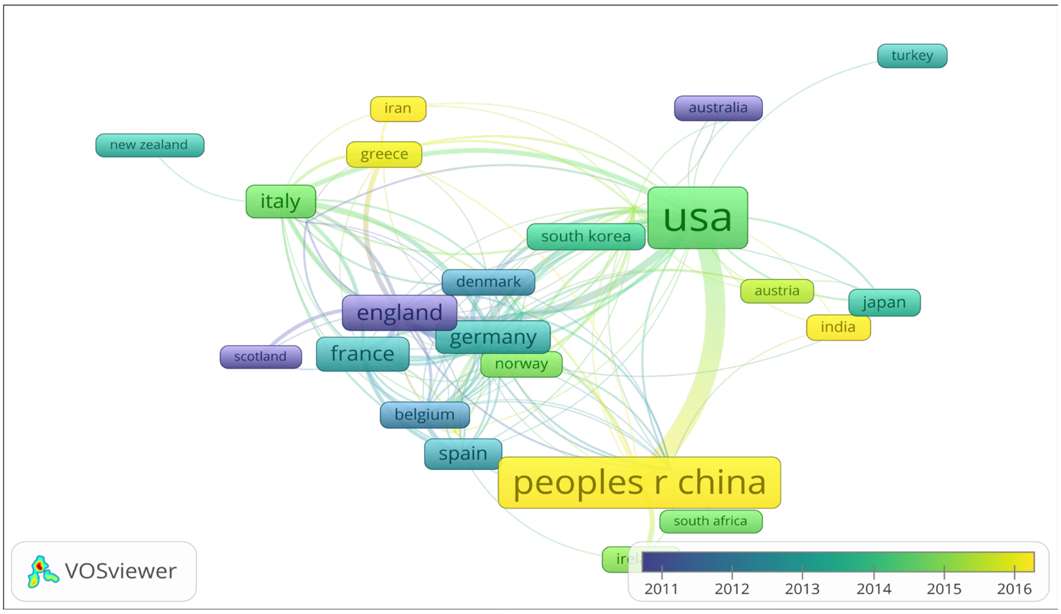

Figure 3.6: Overlay visualization of the relationship between co-authors by country.

The sizes, notes and words as shown in Figure 3.7 represent the weights of the notes. Therefore, bigger words and nodes represent the larger weight. Moreover, the shorter distance between nodes shows a stronger relation, whereas the longer distance shows the weakness of the link. In addition, a thicker line link illustrates that the words have appeared together and there is a strong link. The network has seven clusters, with each cluster denoted by the same colour. The network has a total of 2 684 links and total link strength of 952. Keywords such as ‘contamination’ (102), ‘prediction’ (62), ‘food’ (50), ‘growth’ (41), ‘food safety’ (40), and ‘identification’ have bigger nodes and words, meaning they occurred more frequently.

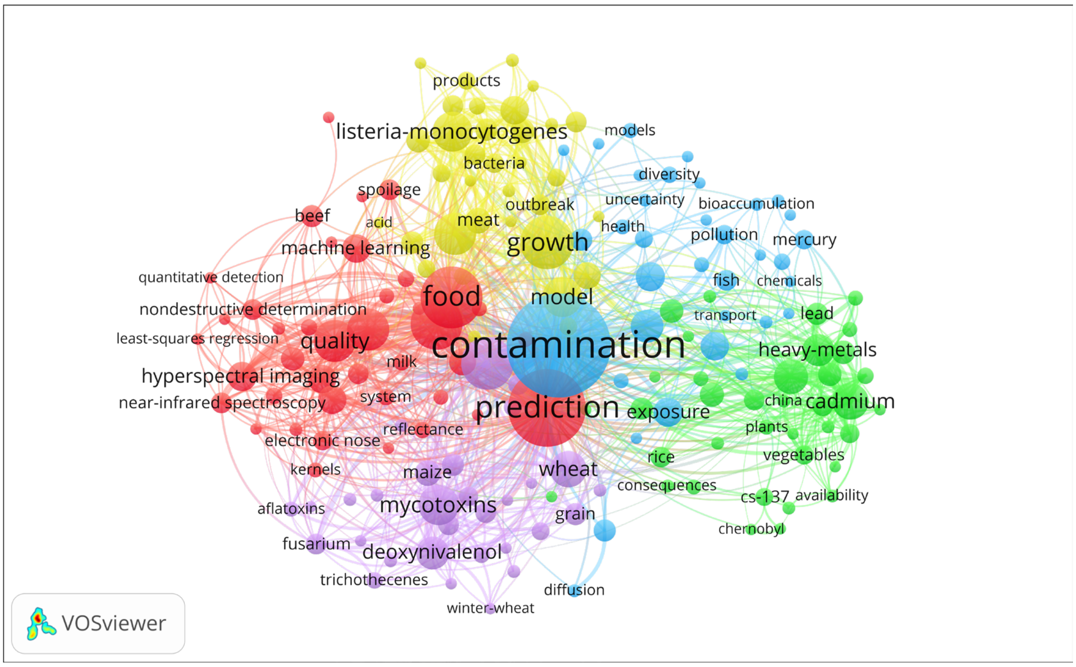

Figure 3.7: Keywords co-occurrence network of food contamination-related publications.

Figures 3.8 to 3.10 show the bibliometric analysis of the citations by authors, organization and country. As shown in Figure 3.8, the results reveal that the most-cited authors are Sun Da-Wen (693 citations) and Van Der Fels-Klerx H.J (378 citations). These two authors are also the most influential regarding the number of publications. In Figure 3.9, the most cited organization is Cranfield University (583), closely followed by the National University of Ireland (538). Also, it can be observed that the Agricultural University of Athens has strong links with the Agricultural Research Service of the United States of America (USDA ARS). As shown in Figure 3.10, the USA occupies the first spot regarding the most-cited countries (2 388 citations), followed by England, which has the second-most citations as a country. Moreover, it is host to the leading organization (Cranfield University) by citation. China and the USA have strong links to being cited. The same relation is observed between England and the Netherlands.

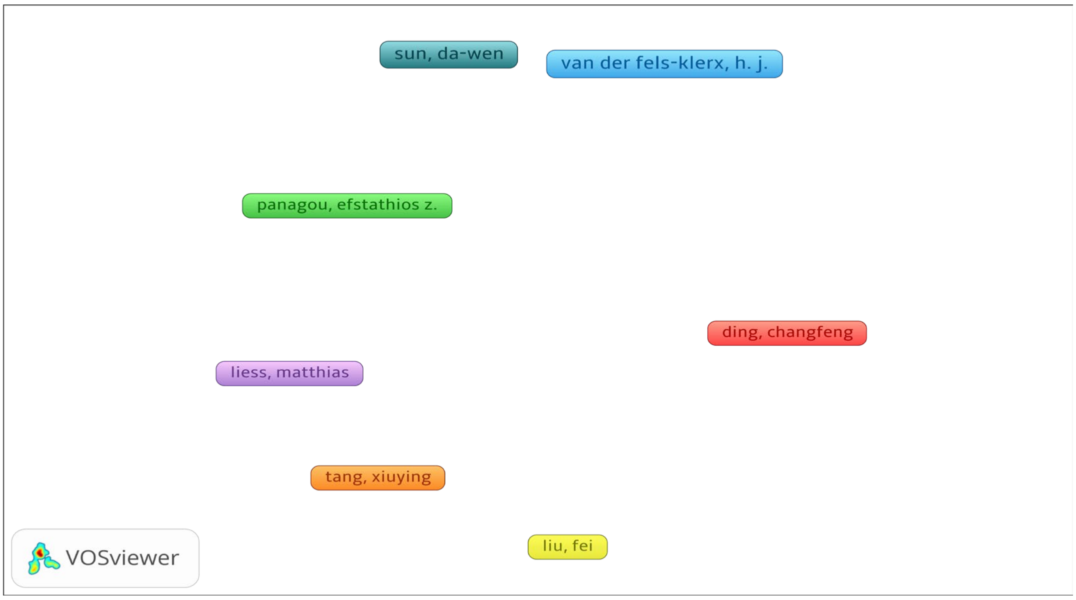

Figure 3.8: Top-cited author.

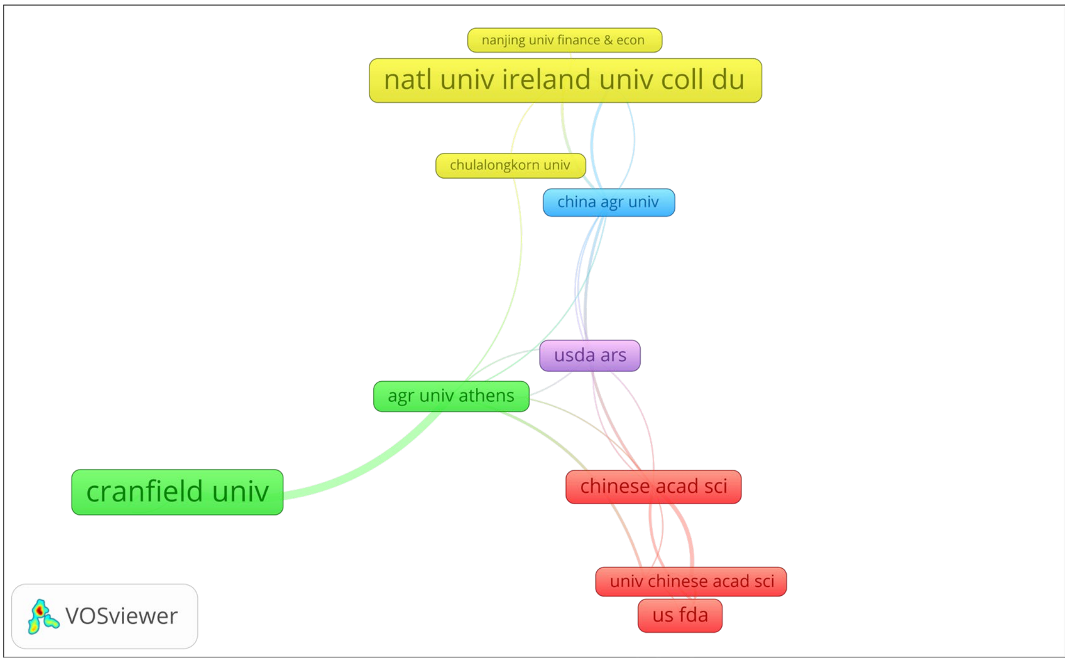

Figure 3.9: Citation by organization.

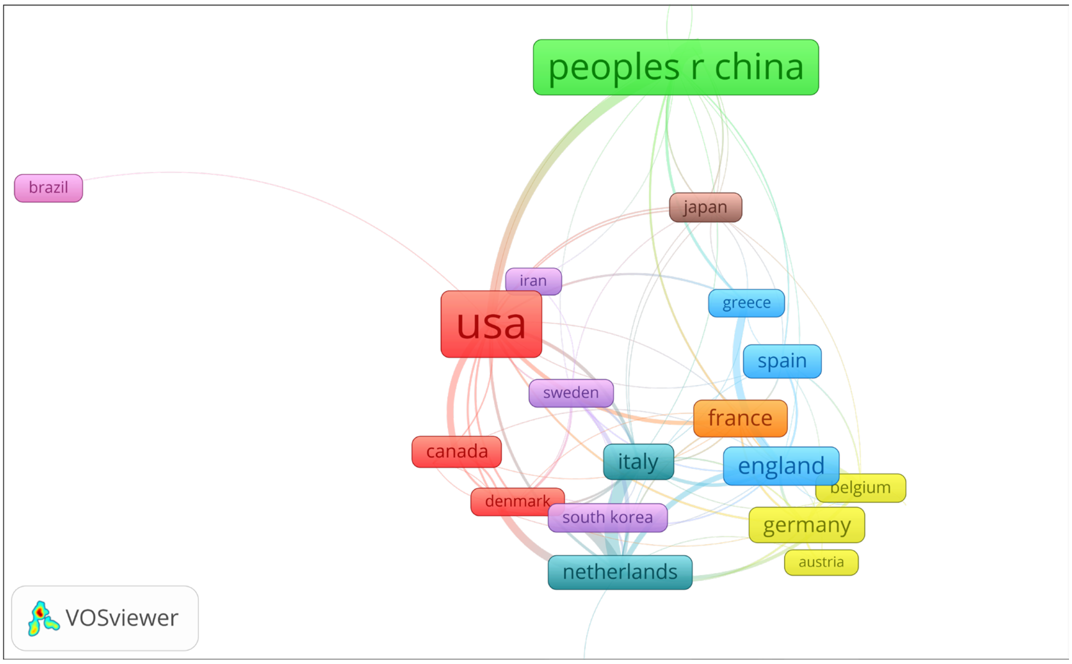

Figure 3.10: Citation by country.

Figures 3.11 and 3.12 below show the bibliographic coupling network visualization of documents and sources, respectively. Fifteen (15) clusters are observed from the bibliometric coupling of documents analysis, whereby cluster 1 contains 73 items; cluster 2 includes 45 items; and cluster 3 has 44 items. The analysis of the bibliometric coupling of sources has three clusters, with the first two having 8 items and the third with 6. The three strongest sources cited include the *Environmental Science and Technology Journal*, which has a total link strength of 47, accounting for 593 citations*; The Science of the Total Environment,* which has a total link strength of 169 with 426 citations; and the *Food additives & Contaminants Part A, Chemistry*, analysis, control, exposure and risk assessment, with a link strength of 198 with 385 citations.

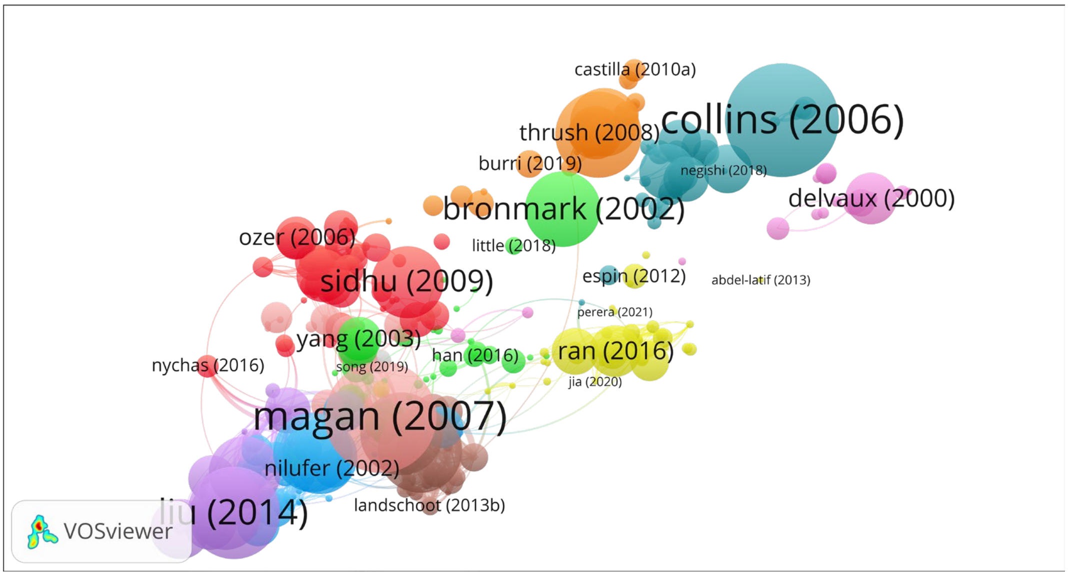

Figure 3.11: Bibliographic coupling of documents**.**

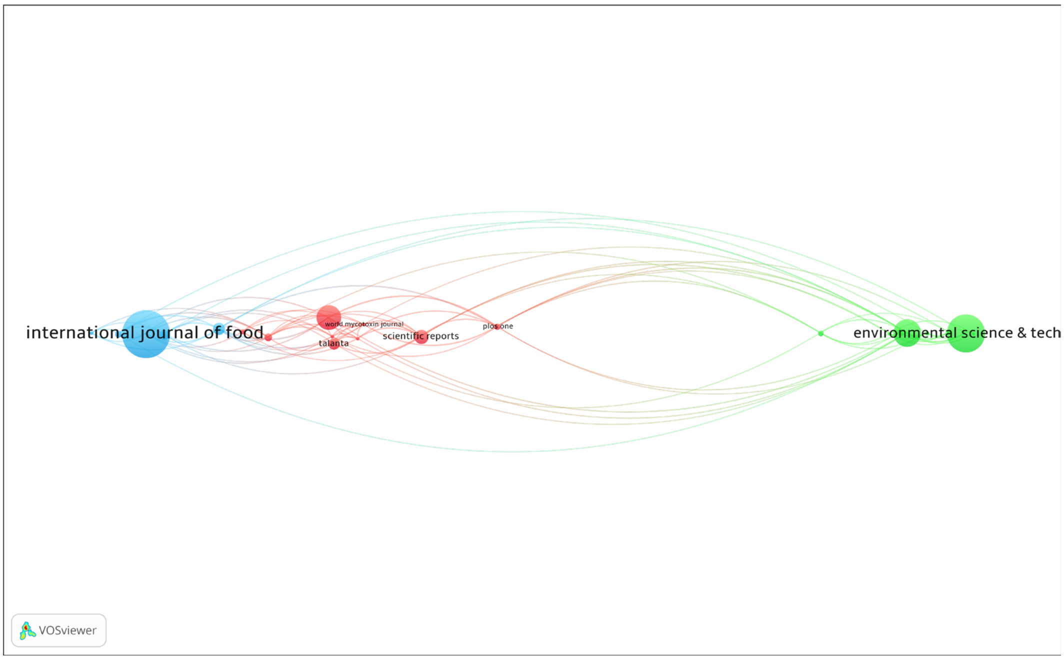

Figure 3.12: Bibliographic coupling of sources.

The bibliometric analysis in this study reveals that from the 516 documents studied, they were cited 10 570 times, with an average *h*-index of 51. Further, each item was cited 20,48 times on average. Figures 3.13 and 3.14 below show the network visualization of bibliometric analysis of the co-citation of sources and authors. The two biggest clusters in Figure 3.13 have 50 and 44 items, respectively. Journals that represent the bulk of the citations are the *International Journal of Food Microbiology, Journal of Food Protection, Environmental Science and*

Technology Journal and *Applied Environmental Microbiology Journal*. Elmasry, G (cluster 1) and Battilani, P (cluster 2) are the most co-cited authors as shown in Figure 3.14.

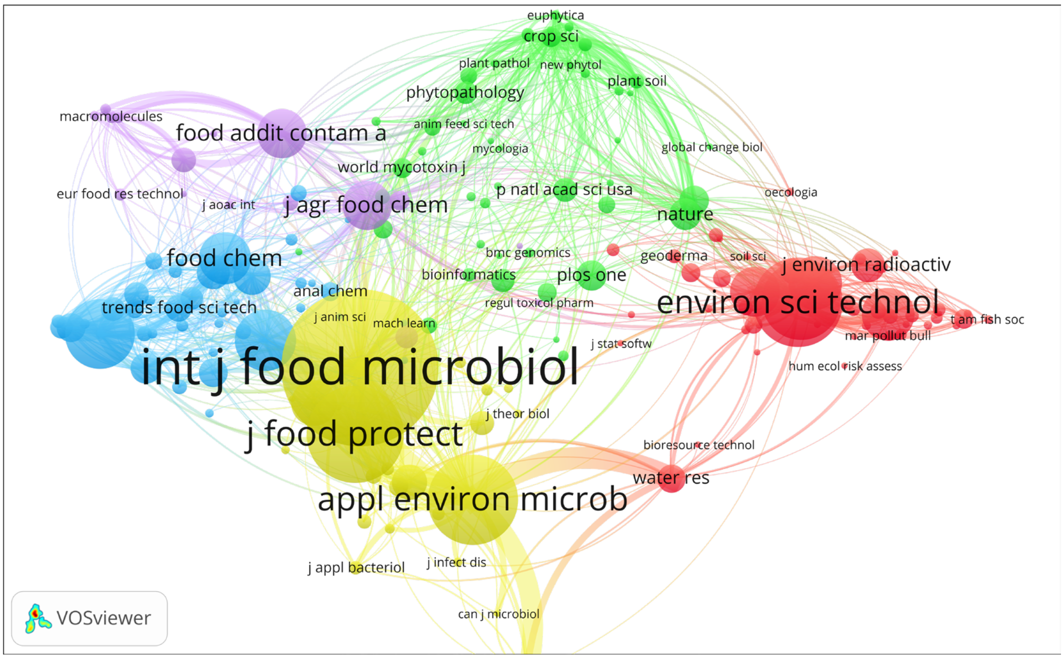

Figure 3.13: Co-citation of sources.

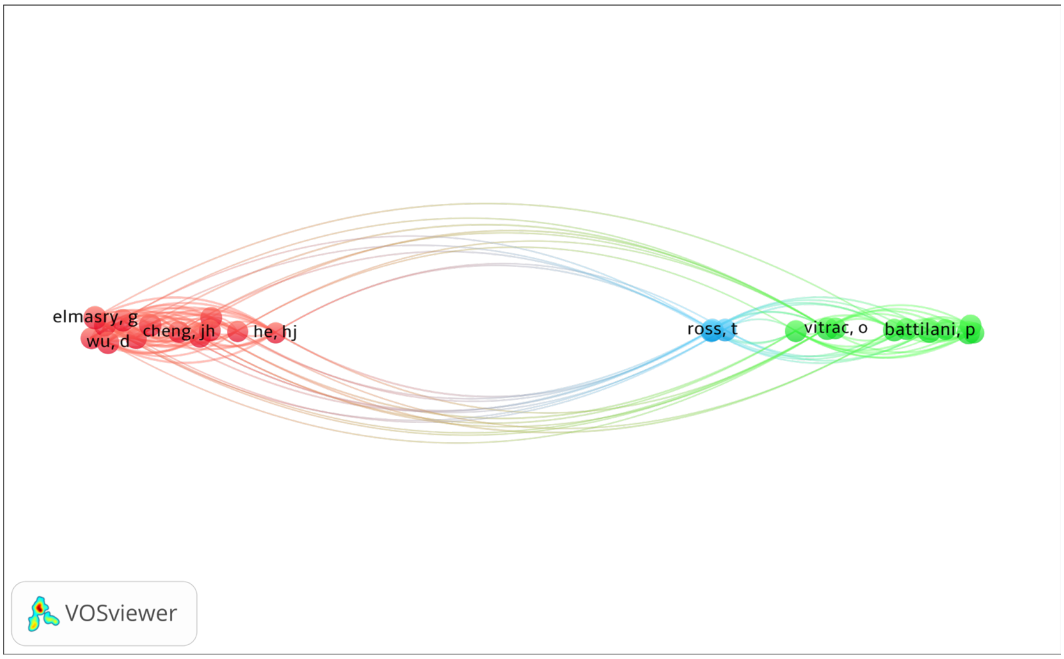

Figure 3.14: Co-citation of authors.

3.4. Discussion

The purpose of this study is to report on the bibliometric research trends on the application of machine learning/intelligent systems in the prediction of food contamination and the surveillance of foodborne diseases. This study consisted of 516 papers extracted from the core collection of the Web of Science database. The indexed databases included topics related to food contamination, prediction, artificial intelligence and machine learning. The bibliometric visualization software (VOSviewer) was used to analyse and visualize research papers from 1996 to January 2021 according to the set criteria. Food contamination and the prediction of foodborne diseases are core public health topics considering the global food consumption and food trade along global borders (Jansen *et al.*, 2020).

The publication of literature relating to food contamination has significant clustering characteristics in food science and technology, and environmental sciences ecology research areas. Moreover, these research areas are more dominant in sources such as the *Science for Total Environment,* the *International Journal of Food Microbiology*, and the *Journal for Food Protection*. In a paper on global research trends in food safety and agriculture, the *Journal of Food Protection* was noted among the representative journals due to its high research output (Hu *et al.*, 2019). In this study, the USA, the People's Republic of China, and England are the most influential countries in food contamination research. Similarly, a study whereby the volume output in this field was led by the above-mentioned countries reinforced their dominance in food-related studies (Hu *et al.*, 2019). In addition, the USA has been ranked first in medical-related fields regarding the number of publications (Sweileh *et al.*, 2016; Zyoud, 2019), and ranked as dominant along with China in food-related studies (Gao *et al.*, 2019). The increase in the number of papers can be attributed to the innovations in computer science, specifically the indexing and development of robust electronic databases (Dos Santos *et al.*, 2019), which further outline that the merger of public health and computer science can produce the desired results in the forecasting of some public health problems. Other causes of the surge in food research can be attributed to the rise in foodborne diseases as a result of global phenomena such as climate change (González *et al.*, 2020). The ever-evolving food industry and the usage of new technology and chemicals in food processing and agriculture also affected the research output in the food industry significantly (Hou and Al-Tabbaa, 2014; Zhang *et al.*, 2015; Ma *et al.*, 2018; Kumar *et al.*, 2019).

Studies on foodborne diseases are increasingly using common themes such as ‘food safety and ‘contamination’. In recent years this has been a trend in public health studies where the food industry is concerned. A plethora of studies has been conducted on the causes of mortality and morbidity in low- to middle-income country populations. Diarrhoeal diseases were documented among the leading illness categories, though the actual causative factors of the diseases were not fully investigated (Clarke *et al.*, 2011). The ever increasing demand for safe food poses a threat to sustainability, considering climatic variations in recent years. The chronic toxicity of mycotoxins such as aflatoxins is largely influenced by climate change in terms of growth and dispersion. This has called for stricter measures worldwide to regulate agricultural produce (Battilani *et al.*, 2016); also, an agenda by health agencies such as the World Health Organization (WHO) and the Centre for Disease Control (CDC) to design systems and intensify surveillance functions in countries without capacity.

The top-cited papers in this study focus on broad topics such as contamination in food from packaging materials and the strategies for preventing chemical contaminants in the food chain and the food industry at large. Chemical toxicity is critical in food safety. Thus, it should be monitored to ensure that wholesome food products are distributed to consumers (Chiesa *et al.*, 2019; Thompson and Darwish, 2019). It is important to note that the top two most influential authors in terms of publication numbers were also part of the top 10 cited publications by featuring at least once.

The application of machine learning has been on the rise in the food industry. As a result, intelligent systems are used in a wide range of applications. A study to compare three modelling approaches for predicting Deoxynivalenol (DON) contamination in winter wheat shows the power of machine learning. The main contribution was that all models in the study provided good accuracy in the prediction of DON in the Netherlands (Liu *et al.* 2018). Moreover, the Bayesian network model was found to be 86% accurate. Also, it was found to be the desired model due to the ease of use, even when input data were incomplete. Researchers in another study regarding sampling monitoring systems for spices found Bayesian networks to be 85% accurate in their prediction (Bouzembrak *et al.*, 2018). The researchers asserted that their model can be effective at border inspection points, markets and consumers. This shows that intelligent systems can be incorporated into surveillance activities regarding food contamination (Van Asselt, Banach and Van der Fels-Klerx, 2018; Manthou *et al.*, 2020). In another study to improve aflatoxin and fumonisins for maize, using Serbia as a case study, researchers (Liu *et al.* 2021) conclude that their forecasting models need robust agronomical data and detailed weather data during the training phase. The vast application of predictive models and artificial intelligence brings a lot of opportunities in the food industry. The Bayesian networks in particular are deemed more transparent regarding understanding the food supply chain when compared with machine-learning approaches (Vågsholm, Arzoomand and Boqvist, 2020).

The key question in using machine-learning approaches in food safety is the selection of the appropriate algorithms to optimize performance and achieve realistic outcomes. Manthou *et al.* (2020) suggest that the implementation of machine-learning approaches needs a thorough knowledge of the range of applications and limitations of the instruments. Also, the results must be evaluated critically. A multidisciplinary approach is required for accurate real-time analyses using big data sets. The correct application of such systems provides robust recommendations and insight that are valuable in making informed decisions timeously. However, researchers caution against the application of predictive tools along the food production chain (farm-to-fork) without understanding and considering the food safety issues. Understandably, technologies in the innovation processes are needed to raise productivity in the food industry. In the early 1990s, the concept of precision agriculture was born in the USA, which aimed at optimizing agricultural production processes. This innovation was necessary to link food safety and food supply using intelligent computational technology (Trivelli *et al.*, 2019).

The increase in population and the quest for improved food quality and safety have given rise to innovations relating to the detection and analysis of food (Bagheri *et al.*, 2020; Marvin and Bouzembrak, 2020). This has led to the development of accurate, rapid and non-destructive methods for food evaluation (Liu, Pu, and Sun 2021). The upward trend of research as shown in Figure 3.2 could be linked to the rising of innovative models in the food industry. Food detection and analysis models have been used extensively in the agri-food industry in recent years. The Convolutional Neural Network (CNN), is effective in detecting low-quality products in food (meat, fish, cereals, fruits, vegetables, etc.) (Liu, Pu and Sun 2021). Moreover, these CNNs have been used to detect crop diseases, thus minimizing loss of food production and maximising profits. The challenges to these models range from the high cost of the hardware to the training of the CNN models, the quality of data provided to the models, etc. (Liu, Pu and Sun, 2021).

Food industry specialists are aware of human errors in detecting defective food products successfully and accurately through the naked eye. This provides an opportunity for computer technology regarding the automation of inspection systems (Tsakanikas *et al.*, 2020). A study by Brosnan and Sun (2004) investigated the application of automated inspection systems using the sensory camera in a system called computer vision. This system has been noted as successful for the objective measurement of agricultural produce. The popularity of computer vision has benefited organizations in cost-effectiveness, speed and accuracy. This technology is used extensively by the top 10 industries, including the food industry. In contrast, there are challenges relating to machine learning, ranging from the high cost of creation and repairs to maintenance and upgrades (Ayed and Hanana 2021; Popa *et al*. 2019).

A study conducted by Song *et al.* (2017) reports the rise in interest to predict morbidity and etiological factors to reduce diseases in populations. In their study, they discuss critical factors that influence the predictive power of intelligent systems. One of the criticisms of Artificial Neural Networks (ANNs) in favour of Deep Neural Networks (DNNs) is that in the prediction of morbidities, time-series ANNs cannot identify the determinants of key influential factors in the cause of diseases. As a result, there is minimal contribution towards disease prevention. In contrast, a paper by Zhang *et al.* (2019) addresses a source prediction problem when they found their model to be 83% accurate and further correctly attributed 7 out of 8 zoonotic disease outbreaks to the correct source. Essentially, advancement in research may allow predictive models to forecast the sources of foodborne outbreaks. Studies show that DNNs have the potential to replace the commonly used machine learning methods such as ANNs to achieve better results regarding food contamination (Song, Zheng and Yang, 2019; Zhou *et al.*, 2019). The advantage over conventional machine learning techniques is that they can learn data representations, transfer learning, use large data sets and still provide better performance and precision (Song *et al.*, 2019; Zhou *et al.*, 2019). As a result, DNNs have attracted various fields such as healthcare, agriculture, medical science, etc.

The objective of this paper is to raise awareness regarding the increased research collaborations between public health using intelligent machine learning systems. In this regard, the prediction of food contamination can be largely facilitated through the use of intelligent systems in the broader field of machine learning. The research trends clearly outline the potential for growth of volume output in the domain of public health, computer science and chemistry collaborations. However, it is important to note that the developing nations also need to be strengthened regarding these fundamental research topics in public health medicine. Literature in infectious diseases has highlighted the application of machine learning methodologies as a growing field with commensurate potential (Wheeler, 2019).

3.5. Limitations

The WoS core collection is a large and reputable database. However, not all research papers added to the WoS are indexed in the core collections and the database may have erroneous data (Yu *et al.*, 2020). Therefore, a possibility that some articles could have been omitted is likely, due to search queries or the sequence of words used to extract data. Also, this study did not consider self-citation as a factor. In some cases, there might have been false negatives and positives in the results, due to the nature of the bibliometric studies (Sweileh *et al.*, 2016; Zyoud, 2019; Sweileh and Moh'd Mansour, 2020). The full names of the authors did not reflect in the database during author analysis. Going forward, multiple databases and in-depth article content analysis will be undertaken to investigate the gaps and transformation of key themes, thus providing an alternative perspective on food contamination and machine learning.

3.6. Conclusions

The study aimed to provide a broad view of the research trends on food contamination and the prediction thereof between January 1996 and January 2021. The study included 516 documents across six document types. The publication records showed a steady upward trend in the first 15 years, with a sharp incline from the year 2013 to 2020. The major research themes were in the field of food science and technology, environmental sciences, ecology, chemistry and agriculture. Moreover, most articles were documented in the top journals, *Science of the Total Environment, International Journal of Food Microbiology,* and *Journal of Food Protection* and *Food Control*. More research is required to bridge the gap between public health, chemistry, and computer science to address the shortfalls in knowledge relating to food contamination and the consequences to the food industry and consumers.

The research trends in machine learning and the application of intelligent systems clearly outline an upward movement. This could be attributed to the ever-increasing incidents in food safety-related matters and the improvement in technology in light of the 4th Industrial Revolution. In recent years, the food industry has been gravitating towards using mechanised systems with intelligent algorithms to meet the demand for safe food more cost-effectively. Therefore, the adoption of intelligent systems has shown significant benefits in controlling potential contaminants, thus reducing the burden of disease and economic loss. The present review has provided evidence of an increase and reception to intelligent systems and their application in the food industry. The evident gap in the reviewed literature is the low usage of advanced intelligent technological systems in developing continents such as Africa. Most developing nations rely on agricultural produce; therefore, investments must be made in sustainable technologies and research to understand and predict the leading food contaminants. This will be advantageous regarding the planning of services, running efficient systems during the food production stages, and ultimately providing safe food to consumers.

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Conflicts of Interest: The authors declare that there is no conflict of interest.

3.7 References

Abdul Rasam, A. R. and Mohd Noor, A. M. (2012) ‘Contribution of GIS and remote sensing technologies for managing foodborne diseases in Malaysia’, *Proceedings – 2012 IEEE Control and System Graduate Research Colloquium, ICSGRC 2012*, (Icsgrc), pp. 258–261. doi: 10.1109/ICSGRC.2012.6287172.

Adisa, O. M. *et al.* (2020) ‘Bibliometric analysis of methods and tools for drought monitoring and prediction in Africa’, *Sustainability (Switzerland)*, 12(16). doi: 10.3390/su12166516.

Amene, E. *et al.* (2016) ‘Variable selection and regression analysis for the prediction of mortality rates associated with foodborne diseases’, *Epidemiology and Infection*, 144(9), pp. 1959–1973. doi: 10.1017/S0950268815003234.

Antoniadis, V. *et al.* (2019) ‘Soil and maize contamination by trace elements and associated health risk assessment in the industrial area of Volos, Greece’, *Environment International*, 124(January), pp. 79–88. doi: 10.1016/j.envint.2018.12.053.

Bagheri, M. *et al.* (2020) ‘Examining plant uptake and translocation of emerging contaminants using machine learning: Implications to food security’, *Science of the Total Environment*, 698, p. 133999. doi: 10.1016/j.scitotenv.2019.133999.

Basavegowda, M. *et al.* (2014) 'An outbreak of staphylococcal food poisoning in a nursing hostel, Mysore, Karnataka', *International Journal of Medicine and Public Health*, 4(3), p. 257. doi: 10.4103/2230-8598.137712.

Battilani, P. *et al.* (2016) 'Aflatoxin B 1 contamination in maize in Europe increases due to climate change', *Scientific Reports*, 6 (December 2015), pp. 1–7. doi: 10.1038/srep24328.

Ben Ayed, R. and Hanana, M. (2021) 'Artificial Intelligence to Improve the Food and Benke, K. and Benke, G. (2018) 'Artificial intelligence and big data in public health', *International Journal of Environmental Research and Public Health*, 15(12). doi: 10.3390/ijerph15122796.

Bennett, S. D. *et al.* (2015) 'Multistate foodborne disease outbreaks associated with raw tomatoes, United States, 1990–2010: A recurring public health problem', *Epidemiology and Infection*, 143(7), pp. 1352–1359. doi: 10.1017/S0950268814002167.

Bouzembrak, Y. *et al.* (2018) 'Application of Bayesian Networks in the development of herbs and spices sampling monitoring system', *Food Control*, 83, pp. 38–44. doi: 10.1016/j.foodcont.2017.04.019.

Brosnan, T. and Sun, D. W. (2004) 'Improving quality inspection of food products by computer vision – A review', *Journal of Food Engineering*, 61(1 SPEC.), pp. 3–16. doi: 10.1016/S0260-8774(03)00183-3.

Chiesa, L. M. *et al.* (2019) 'Food risk characterization from exposure to persistent organic pollutants and metals contaminating eels from an Italian lake', *Food Additives and Contaminants - Part A Chemistry, Analysis, Control, Exposure and Risk Assessment*, 36(5), pp. 779–788. doi: 10.1080/19440049.2019.1591642.

Clarke, M. F. *et al.* (2011) 'Direct and indirect impact on rotavirus positive and all-cause gastroenteritis hospitalisations in South Australian children following the introduction of rotavirus vaccination', *Vaccine*, 29(29–30), pp. 4663–4667. doi: 10.1016/j.vaccine.2011.04.109.

Dhital, S. and Rupakheti, D. (2019) 'Bibliometric analysis of global research on air pollution and human health: 1998–2017’, *Environmental Science and Pollution Research*, 26(13), pp. 13103–13114. doi: 10.1007/s11356-019-04482-x.

Djekic, I. *et al.* (2014) ‘Food hygiene practices in different food establishments’, *Food Control*, 39(1), pp. 34–40. doi: 10.1016/j.foodcont.2013.10.035.

Dos Santos, B. S. *et al.* (2019) ‘Data mining and machine learning techniques applied to public health problems: A bibliometric analysis from 2009 to 2018’, *Computers and Industrial Engineering*, 138(April), p. 106120. doi: 10.1016/j.cie.2019.106120.

Ebel, E. D. *et al.* (2016) ‘Comparing characteristics of sporadic and outbreak-associated foodborne Illnesses, United States, 2004-2011’, *Emerging Infectious Diseases*, 22(7), pp. 1193–1200. doi: 10.3201/eid2207.150833.

Ernstoff, A. *et al.* (2019) ‘Challenges of including human exposure to chemicals in food packaging as a new exposure pathway in life cycle impact assessment’, *International Journal of Life Cycle Assessment*, 24(3), pp. 543–552. doi: 10.1007/s11367-018-1569-y.

Feng, C. *et al.* (2021) ‘Evaluation and application of machine learning-based retention time prediction for suspect screening of pesticides and pesticide transformation products in LC-HRMS’, *Chemosphere*, 271, p. 129447. doi:10.1016/j.chemosphere.2020.129447.

Ford, L. *et al.* (2015) ‘Approaches to the surveillance of foodborne disease: A review of the evidence’, *Foodborne Pathogens and Disease*, 12(12), pp. 927–936. doi: 10.1089/fpd.2015.2013.

Gao, Y. *et al.* (2019) ‘Global trends and future prospects of e-waste research: a bibliometric analysis’, *Environmental Science and Pollution Research*, 26(17), pp. 17809–17820. doi: 10.1007/s11356-019-05071-8.

Geueke, B., Groh, K. and Muncke, J. (2018) ‘Food packaging in the circular economy: Overview of chemical safety aspects for commonly used materials’, in A. M. Holban, and A. M. Grumezescu (eds) *Journal of Cleaner Production*. Elsevier Ltd, pp. 491–505. doi: 10.1016/j.jclepro.2018.05.005.

González, N. *et al.* (2020) ‘Meat consumption: Which are the current global risks? A review of recent (2010–2020) evidences', *Food Research International*, 137(April), p. 109341. doi: 10.1016/j.foodres.2020.109341.

Gould, L. H. *et al.* (2013) 'Surveillance for Foodborne Disease Outbreaks — United States, 1998–2008', 62(2), pp. 1–34. doi: 10.2307/24806072.

Gumbo, A. *et al.* (2015) 'Staphylococcus aureus food poisoning among Bulawayo City Council employees, Zimbabwe, 2014', *BMC Research Notes*, 8(1), pp. 1–7. doi: 10.1186/s13104-015-1490-4.

Havelaar, A. H. *et al.* (2015) 'World Health Organization Global Estimates and Regional Comparisons of the Burden of Foodborne Disease in 2010', *PLoS Medicine*, 12(12), pp. 1–24. doi: 10.1371/journal.pmed.1001923.

Hoffmann, S., Maculloch, B. and Batz, M. (2015) 'Economic burden of major foodborne illnesses acquired in the United States', *Economic Cost of Foodborne Illnesses in the United States*, (140), pp. 1–74.

Hou, D. and Al-Tabbaa, A. (2014) 'Sustainability: A new imperative in contaminated land remediation', *Environmental Science and Policy*, 39, pp. 25–34. doi: 0.1016/j.envsci.2014.02.003.

Hu, K. *et al.* (2019) 'Global research trends in food safety in agriculture and industry from 1991 to 2018: A data-driven analysis', *Trends in Food Science and Technology*, 85(September 2018), pp. 262–276. doi: 10.1016/j.tifs.2019.01.011.

Jansen, T. *et al.* (2020) '"All chemical substances are harmful." public appraisal of uncertain risks of food additives and contaminants', *Food and Chemical Toxicology*, 136(October 2019), p. 110959. doi: 10.1016/j.fct.2019.110959.

Käferstein, F. (2003) 'Foodborne diseases in developing countries: Aetiology, epidemiology and strategies for prevention', *International Journal of Environmental Health Research*, 13(SUPPL. 1), pp. 161–168. doi: 10.1080/0960312031000102949.

Kumar, M. *et al.* (2019) 'Antibiotics bioremediation: Perspectives on its ecotoxicity and resistance', *Environment International*, 124 (December 2018), pp. 448–461. doi: 10.1016/j.envint.2018.12.065.

Lake, I. R. (2017) ‘Food-borne disease and climate change in the United Kingdom’, *Environmental Health: A Global Access Science Source*, 16 (Suppl 1), pp. 53–59. doi: 10.1186/s12940-017-0327-0.

Latino, M. E., Menegoli, M. and Corallo, A. (2020) ‘Food label design – exploring the literature’, *British Food Journal*, 122(3), pp. 766–778. doi: 10.1108/BFJ-06-2019-0452.

Lee, B. (2017) ‘Foodborne disease and the need for greater foodborne disease surveillance in the Caribbean’, *Veterinary Sciences*, 4(3). doi: 10.3390/vetsci4030040.

Li, K., Rollins, J. and Yan, E. (2018) ‘Web of Science use in published research and review papers 1997–2017: a selective, dynamic, cross-domain, content-based analysis’, *Scientometrics*, 115(1), pp. 1–20. doi: 10.1007/s11192-017-2622-5.

Liao, H. *et al.* (2018) ‘A bibliometric analysis and visualization of medical big data research’, *Sustainability (Switzerland)*, 10(1), pp. 1–18. doi: 10.3390/su10010166.

Liu, C. *et al.* (2018) ‘Comparison of three modelling approaches for predicting deoxynivalenol contamination in winter wheat’, *Toxins*, 10(7), pp. 1–15. doi: 10.3390/toxins10070267.

Liu, N. *et al.* (2021) ‘Improved Aflatoxins and Fumonisins Forecasting Models for Maize (PREMA and PREFUM), Using Combined Mechanistic and Bayesian Network Modeling—Serbia as a Case Study’, *Frontiers in Microbiology*, 12 (April), pp. 1–9. doi: 10.3389/fmicb.2021.643604.

Liu, W. and Liao, H. (2017) ‘A Bibliometric Analysis of Fuzzy Decision Research During 1970–2015’, *International Journal of Fuzzy Systems*, 19(1). doi: 10.1007/s40815-016-0272-z.

Liu, Y., Pu, H. and Sun, D. W. (2021) ‘Efficient extraction of deep image features using convolutional neural network (CNN) for applications in detecting and analysing complex food matrices’, *Trends in Food Science and Technology*, 113 (April), pp. 193–204. doi: 10.1016/j.tifs.2021.04.042.

Ma, Y. *et al.* (2018) ‘Remediating potentially toxic metal and organic co-contamination of soil by combining in situ solidification/stabilization and chemical oxidation: Efficacy, mechanism, and evaluation', *International Journal of Environmental Research and Public Health*, 15(11), pp. 1–19. doi: 10.3390/ijerph15112595.

Magalhães, A. E. V. *et al.* (2019) 'Food traceability technologies and foodborne outbreak occurrences', *British Food Journal*, 121(12), pp. 3362–3379. doi: 10.1108/BFJ-02-2019-0143.

Manes, M. R., Liu, L. C. and Dworkin, M. S. (2013) 'Baseline knowledge survey of restaurant food handlers in Suburban Chicago: Do restaurant food handlers know what they need to know to keep consumers safe?', *Journal of Environmental Health*, 76(1), pp. 18–26.

Manthou, E. *et al.* (2020) 'Application of spectroscopic and multispectral imaging technologies on the assessment of ready-to-eat pineapple quality: A performance evaluation study of machine learning models generated from two commercial data analytics tools', *Computers and Electronics in Agriculture*, 175(May), p. 105529. doi: 10.1016/j.compag.2020.105529.

Marvin, H. J. P. and Bouzembrak, Y. (2020) 'A system approach towards prediction of food safety hazards: Impact of climate and agrichemical use on the occurrence of food safety hazards', *Agricultural Systems*, 178 (November 2019), p. 102760. doi: 10.1016/j.agsy.2019.102760.

Mayet, A. *et al.* (2011) 'Epidemiology of food-borne disease outbreaks in the French armed forces: A review of investigations conducted from 1999 to 2009', *Journal of Infection*, 63(5), pp. 370–374. doi: 10.1016/j.jinf.2011.08.003.

Mehdi, Y. *et al.* (2018) 'Use of antibiotics in broiler production: Global impacts and alternatives', *Animal Nutrition*, 4(2), pp. 170–178. doi: 10.1016/j.aninu.2018.03.002.

Meng, L. *et al.* (2020) 'Knowledge atlas on the relationship between urban street space and residents' health-a bibliometric analysis based on vos viewer and cite space', *Sustainability (Switzerland)*, 12(6). doi: 10.3390/su12062384.

Mongeon, P. and Paul-Hus, A. (2016) 'The journal coverage of Web of Science and Scopus: a comparative analysis', *Scientometrics*, 106(1), pp. 213–228. doi: 10.1007/s11192-

015-1765-5.

Na, W. *et al.* (2016) 'Incidences of Waterborne and Foodborne Diseases After Meteorologic Disasters in South Korea', *Annals of Global Health*, 82(5), pp. 848–857. doi: 10.1016/j.aogh.2016.10.007.

Nosratabadi, S. *et al.* (2021) 'Prediction of Food Production Using Machine Learning Algorithms of Multilayer Perceptron and ANFIS', *Agriculture*, 11(5), p. 408. doi: 10.3390/agriculture11050408.

Obileke, K. C. *et al.* (2020) 'Bioenergy from bio-waste: a bibliometric analysis of the trend in scientific research from 1998–2018', *Biomass Conversion and Biorefinery*. doi: 10.1007/s13399-020-00832-9.

Osei-Tutu, B. and Anto, F. (2016) 'Trends of reported foodborne diseases at the Ridge Hospital, Accra, Ghana: A retrospective review of routine data from 2009-2013', *BMC Infectious Diseases*, 16(1). doi: 10.1186/s12879-016-1472-8.

Popa, A. *et al.* (2019) 'An intelligent IoT-based food quality monitoring approach using low-cost sensors', *Symmetry*, 11(3). doi: 10.3390/sym11030374.

Secinaro, S. and Calandra, D. (2021) 'Halal food: structured literature review and research agenda', *British Food Journal*, 123(1), pp. 225–243. doi: 10.1108/BFJ-03-2020-0234.

Shonhiwa, A. M. *et al.* (2019) 'A review of foodborne diseases outbreaks reported to the outbreak response unit, national institute for communicable diseases, South Africa, 2013–2017', *International Journal of Infectious Diseases*, 79(2019), p. 73. doi: 10.1016/j.ijid.2018.11.186.

Song, Q. *et al.* (2017) 'An evolutionary deep neural network for predicting morbidity of gastrointestinal infections by food contamination', *Neurocomputing*, 226(November 2016), pp. 16–22. doi: 10.1016/j.neucom.2016.11.018.

Song, Q., Zheng, Y. J. and Yang, J. (2019) 'Effects of food contamination on gastrointestinal morbidity: Comparison of different machine-learning methods', *International Journal of Environmental Research and Public Health*, 16(5). doi: 10.3390/ijerph16050838.

Sweileh, W. M. *et al.* (2016) 'Bibliometric analysis of publications on Campylobacter: (2000-

2015)', *Journal of health, population, and nutrition*, 35(1), p. 39. doi: 10.1186/s41043-016-0076-7.

Sweileh, W. M. and Moh'd Mansour, A. (2020) 'Bibliometric analysis of global research output on antimicrobial resistance in the environment (2000–2019)', *Global Health Research and Policy*, 5(1). doi: 10.1186/s41256-020-00165-0.

Tchatchouang, C. D. K. *et al.* (2020) 'Listeriosis outbreak in South Africa: A comparative analysis with previously reported cases worldwide', *Microorganisms*, 8(1). doi: 10.3390/microorganisms8010135.

Thompson, L. A. and Darwish, W. S. (2019) 'Environmental Chemical Contaminants in Food: Review of a Global Problem', *Journal of Toxicology*, 2019, pp. 1–14. doi: 10.1155/2019/2345283.

Trivelli, L. *et al.* (2019) 'From precision agriculture to Industry 4.0: Unveiling technological connections in the agrifood sector', *British Food Journal*, 121(8), pp. 1730–1743. doi: 10.1108/BFJ-11-2018-0747.

Tsakanikas, P. *et al.* (2020) 'A machine learning workflow for raw food spectroscopic classification in a future industry', *Scientific Reports*, 10(1), pp. 1–11. doi: 10.1038/s41598-020-68156-2.

Vågsholm, I., Arzoomand, N. S. and Boqvist, S. (2020) 'Food Security, Safety, and Sustainability – Getting the Trade-Offs Right', *Frontiers in Sustainable Food Systems*, 4(February), pp. 1–14. doi: 10.3389/fsufs.2020.00016.

Van Asselt, E. D., Banach, J. L. and Van der Fels-Klerx, H. J. (2018) 'Prioritization of chemical hazards in spices and herbs for European monitoring programs', *Food Control*, 83, pp. 7–17. doi: 10.1016/j.foodcont.2016.12.023.

Van Eck, N. J. and Waltman, L. (2010) 'Software survey: VOSviewer, a computer program for bibliometric mapping', *Scientometrics*, 84(2), pp. 523–538. doi: 10.1007/s11192-009-0146-3.

Vila-Lopez, N. and Küster-Boluda, I. (2020) 'A bibliometric analysis on packaging research: towards sustainable and healthy packages', *British Food Journal*, 123(2), pp. 684–

701. doi: 10.1108/BFJ-03-2020-0245.

Wang, X. *et al.* (2018) ‘A Bayesian approach to real-time monitoring and forecasting of Chinese foodborne diseases’, *International Journal of Environmental Research and Public Health*, 15(8). doi: 10.3390/ijerph15081740.

Weiser, A. A. *et al.* (2016) ‘FoodChain-lab: Tracing Software Supporting Foodborne Disease Outbreak Investigations’, *Procedia Food Science*, 7, pp. 101–104. doi: 10.1016/j.profoo.2016.02.097.

Wheeler, N. E. (2019) ‘Tracing outbreaks with machine learning’, *Nature Reviews Microbiology*, 17(5), p. 269. doi: 10.1038/s41579-019-0153-1.

Yang, W., Zhang, J. and Ma, R. (2020) ‘The prediction of infectious diseases: A bibliometric analysis’, *International Journal of Environmental Research and Public Health*, 17(17), pp. 1–19. doi: 10.3390/ijerph17176218.

Yi, F., Yang, P. and Sheng, H. (2016) ‘Tracing the scientific outputs in the field of Ebola research based on publications in the Web of Science’, *BMC Research Notes*, 9(1), pp. 1–7. doi: 10.1186/s13104-016-2026-2.

Yu, D. and Liao, H. (2016) ‘Visualization and quantitative research on intuitionistic fuzzy studies’, *Journal of Intelligent and Fuzzy Systems*, 30(6), pp. 3653–3663. doi: 10.3233/IFS-162111.

Yu, Y. *et al.* (2020) ‘A bibliometric analysis using VOSviewer of publications on COVID-19’, *Annals of Translational Medicine*, 8(13), pp. 816–816. doi: 10.21037/atm-20-4235.

Zhang, S. *et al.* (2019) ‘Zoonotic source attribution of Salmonella enterica serotype typhimurium using genomic surveillance data, United States’, *Emerging Infectious Diseases*, 25(1), pp. 82–91. doi: 10.3201/eid2501.180835.

Zhang, X. *et al.* (2015) ‘Impact of soil heavy metal pollution on food safety in China’, *PLoS ONE*, 10(8), pp. 1–14. doi: 10.1371/journal.pone.0135182.

Zhou, L. *et al.* (2019) ‘Application of Deep Learning in Food: A Review’, *Comprehensive Reviews in Food Science and Food Safety*, 18(6), pp. 1793–1811. doi: 10.1111/1541-

4337.12492.

Zhu, J. and Liu, W. (2020) ‘A tale of two databases: the use of Web of Science and Scopus in academic papers’, *Scientometrics*, 123(1), pp. 321–335. doi: 10.1007/s11192-020-03387-8.

Zyoud, S. H. (2019) ‘Global scientific trends on aflatoxin research during 1998-2017: a bibliometric and visualized study’, *Journal of Occupational Medicine and Toxicology*, 14(1), pp. 1–11. doi: 10.1186/s12995-019-0248-7.

CHAPTER 4:

AN OVERVIEW OF FOOD CONTAMINATION, DETECTION, AND SURVEILLANCE: CURRENT AND FUTURE TRENDS

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Abstract

Food contamination has proven to be overwhelming to public health authorities and their surveillance systems. The global response to this challenge has been met with slow progress, specifically in developing nations regarding outbreak investigations. This is exacerbated by a lack of capacity within the public health system. This review focuses on food contamination, surveillance, and the general consequences of inefficient systems. Research trends suggest there have been significant strides in food contamination research through innovations and adaptive systems. Moreover, the more developed fields in food safety studies have given rise to fundamental themes that need further exploration. These include exposure to toxic hazards, risk assessments and food contamination from environmental sources. Ultimately, major improvements are needed to protect populations through organized systems through public and private partnerships. This can be achieved through collaborations between the food industry and regulatory bodies.

Keywords: food contamination, food safety, foodborne disease surveillance.

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4.1. Introduction

Disease surveillance and exposure assessments are critical key performance indicators of an effective and efficient public health system. A plethora of studies have been conducted on the causes of mortality and morbidity in low to middle-income country populations. Most studies have documented the potential risks to human health via food contamination in both formal and informal settings (Ankar-Brewoo *et al.*, 2020). The contamination stems from various sources. It can be from persistent environmental hazards such as pesticides and heavy metals (Bai and Ogbourne, 2016; Ankar-Brewoo *et al.*, 2020; Lebelo *et al.*, 2021); substances such as Clenbuterol (Thevis *et al.*, 2013); and microbial hazards such as Listeria monocytogenes (Nerín, Aznar and Carrizo, 2016; Camargo *et al.*, 2017). Diarrhoeal diseases are documented among the leading illness categories, though the actual causative factors of the diseases are not fully investigated (Clarke *et al.*, 2011; Berking *et al.*, 2019). This leads to agendas by health agencies such as the World Health Organization (WHO) and the Centre for Disease Control (CDC) to design systems and intensify surveillance and compliance functions in countries without capacity.

In the 19th century, Europe and North America were the leading frontiers in reporting weekly incidences of diseases. The data collected were reported to have been helpful in policy formulation and assessing the impact of certain interventions (Simonsen *et al.*, 2016; Lebelo and Van Wyk, 2019a). In the 20th century, technological innovations and advances in microbiology led to laboratory-based surveillance. Microbiological concepts and principles in surveillance have been enhanced with faster detection tools and on-site isolation and detection techniques. Furthermore, new technologies in diagnostics such as PFGE subtyping (Hoelzer *et al.*, 2018) and the National Molecular Tracing Network have haven added in recent years (Li *et al.*, 2018). Additionally, these technologies require substantial investments in infrastructure development, training, policy adjustments and public-private partnerships (Hoelzer *et al.*, 2018; Nayak and Waterson, 2019). Public health surveillance is perceived as a pinnacle of effective public health policy, which in turn transforms developing nations in the battle against foodborne illnesses (Simonsen *et al.*, 2016; Hoelzer *et al.*, 2018; Ramirez-Hernandez *et al.*, 2020). Therefore, these technologies have proven effective as part of a surveillance system.

To date, various studies have largely focused on the prevalence of HIV and different strains of Mycobacterium tuberculosis in public health. Understandably, the two mentioned illnesses are significant contributors to the burden of disease to the universal public health spectrum and economy. However, foodborne diseases (FBDs) have been the leading cause of disease in developing nations amongst susceptible population groups (Lebelo and Van Wyk, 2019b; Focker and Van der Fels-Klerx, 2020). Thus, provision needs to be made to flatten the curve of exposure to hazards and eventually cause a decline through timeous surveillance and forecasting. Disease forecasting is an innovation that public health professionals appreciate, considering the range of diseases they are expected to protect the public against. The inception of machine learning has helped different spheres of government globally to predict health outcomes and possible relationships between diseases and environmental conditions (Benke and Benke, 2018; Wang *et al.*, 2018; Yang *et al.*, 2020). Furthermore, more studies need to be conducted to explore and fully utilise the prediction power of adaptive systems in the advancement of infectious disease surveillance (Jansen *et al.*, 2020).

This paper highlights major challenges in food contamination, detection and surveillance. Moreover, it aims to set the scene for understanding the key contributing factors to the manifestation of FBDs and their impact. In addition, the major drawbacks of surveillance systems are discussed.

4.2. Methods

This review was conducted using peer-reviewed papers focusing on food contamination, detection and surveillance research. The literature search was completed using a combination of Google scholar and the Web of Science (WoS) core collection database. The WoS is reputable in documenting scientific studies across different disciplines (Li, Rollins and Yan, 2018; Pandey *et al.*, 2018; Secinaro and Calandra, 2021; Tong and Song, 2021). The keywords that were used to generate results included: food contamination, food contaminants, and foodborne disease surveillance, as illustrated in Figure 4.1. The papers included in the study met the following criteria: English, document format (Abstract, conference proceedings, full-text research papers). Moreover, the selected papers had to contain explicit information as required by the researchers. The papers from both Google scholar and WoS were analysed thematically and narrated by the researcher. Further analysis of WoS exported files was thematically mapped using the R package (bibliometrix) and VOSviewer version 1.6.15 software

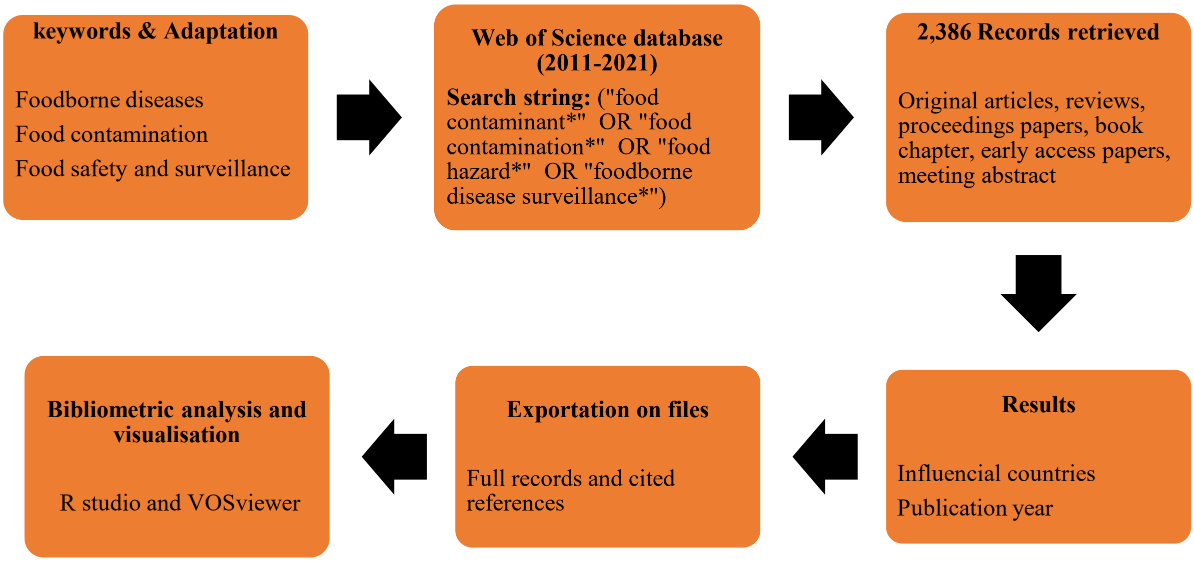

Figure 4.1: Bibliometric data search flow methodology for thematic analysis. This is an illustration of the research process from data collection to final analysis.

4.3. The burden of foodborne diseases on the public health system

In 2015, the World Health Organization (WHO) embarked on a study to estimate the global and regional burden of FBDs. In this particular study, the causes of infection under investigation were bacteria, protozoa and viruses. Food contamination was found to be the leading cause of disease, particularly in children under five years (Convertino *et al*, 2014; Havelaar *et al.*, 2015). Furthermore, the gloomy results were evident in developing nations in Africa, followed by Southeast Asian countries. This shows a possible link between the socioeconomic status of the region and the increased infection rates (Havelaar *et al.*, 2015). In recent years, researchers have expressed that there is no significant difference between the current factors driving emerging food safety risks. Essentially, population dynamics, economic factors, lack of resources and environmental variability remain the main driving forces of existing and emerging food safety risks (Kendall *et al.*, 2018; Massomo, 2020). Figure 2 shows the increase in food contamination and surveillance research in the last decade. Figure 3 depicts the top 10 leading countries. It further highlights the dominance of the United States of America (USA) and the People's Republic of China in food contamination research

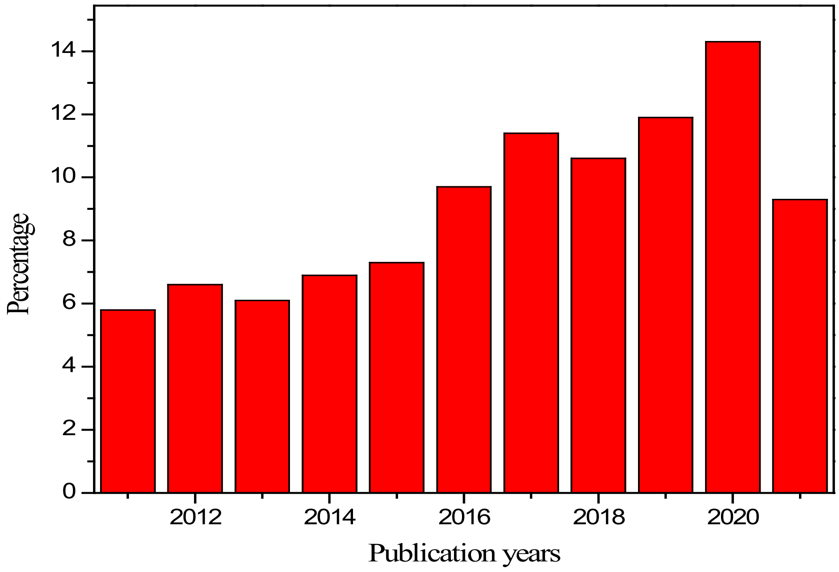

Figure 4.2: Annual number of scientific publications from 2011-2021, using the search terms, "food contaminant*" OR "food contamination*" OR "food hazard*" OR "foodborne disease surveillance*".

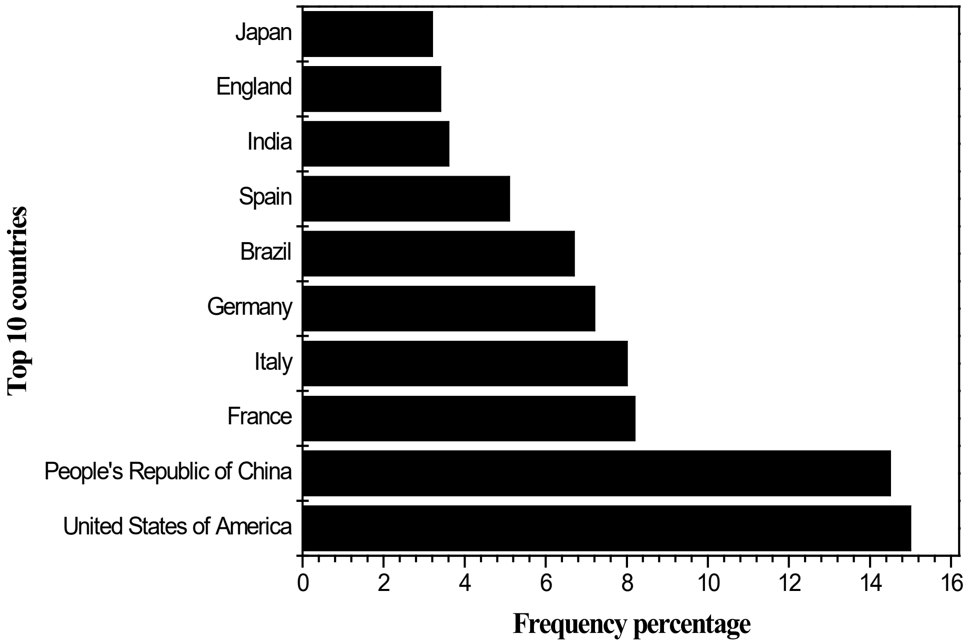

Figure 4.3: Top 10 leading countries from 2011-2021, using the search terms, "food contaminant*" OR "food contamination*" OR "food hazard*" OR "foodborne disease surveillance*". Data analysis was completed using the Web of Science core collection databases on 27 July 2021.

Foodborne diseases are classified as notifiable medical conditions in South Africa. Researchers from the National Institute for Communicable Diseases (NICD) report that the burden of diseases in South Africa is still uncertain, due to factors such as underreporting and lack of capacity regarding epidemiological data collection and outbreak investigations (Shonhiwa *et al.*, 2019). In their study between the years 2013 and 2017, they reported 11 155 people falling ill due to FBDs, with 78% (8 680) visiting the hospital. Furthermore, most of the outbreaks were reported in the warmer months of the year, which could likely be attributed to food spoilage due to climatic conditions. This shows the significance of the numbers that can burden primary healthcare in terms of medical care and the usage of essential medicines.

Foodborne diseases are often underreported, due to the delays and usually reactive public health systems (Amene *et al.*, 2016; Osei-Tutu and Anto, 2016; Faour-Klingbeil and Todd, 2020). This is a reality in developing countries where systems are usually inefficient with limited resources (Mayet *et al.*, 2011; Gould *et al.*, 2013; Shonhiwa *et al.*, 2019). This is further supported by a study in South Africa on the use of mobile applications to improve the diagnosis of pesticide poisonings. The researchers discovered significant underreporting to the National Department of Health by health professionals (Kabanda and Rother, 2019). In other studies, it was discovered that patients often delay seeking medical attention, due to unawareness of the extent of the disease. These delays could alter the incident numbers reported and the timeliness of controlling public health disasters (Wang *et al.*, 2018).

4.4. Case reporting and routine health information systems

Disease surveillance is an information-based activity involving the collection, analysis, interpretation and dissemination of large volumes of data originating from a variety of sources (Gould *et al.*, 2013; Tchatchouang *et al.*, 2020; Velmovitsky *et al.*, 2021). It is an epidemiological practice by which the spread of disease is monitored to establish patterns of progression (Ebel *et al.*, 2016; Lebelo and Van Wyk, 2019b). The main role of disease surveillance is to predict, observe and minimize the harm caused by outbreaks. In addition, it increases knowledge about which factors contribute to such circumstances (Althouse *et al.*, 2015; Wang *et al.*, 2017; Gilbert, Degeling and Johnson, 2019). A key part of modern disease surveillance is the practice of disease case reporting (Gilbert, Degeling and Johnson, 2019). In recent years, more robust techniques such as precision medicine and precision public health have been introduced to bolster surveillance systems through aggregation, integration and analysis of Big Data (Khoury *et al.*, 2020; Velmovitsky *et al.*, 2021). A standardized surveillance information system is beneficial when it is made available in different spheres of government, i.e., national, regional and local. Therefore, all professionals in healthcare service delivery should be trained meticulously on matters relating to policy and data collection (Nnebue *et al.*, 2012; Draeger *et al.*, 2019). Health information is an essential communication point in forecasting and responding to disease outbreaks and incidents of regional, national and international significance (Baquero *et al.*, 2018). Moreover, digitization at the point of the collection has proven to be innovative and effective for health systems. This implies that health professionals could have access to real-time surveillance data at their disposal. Such fast-paced data flow increases the need for more applications and simulated exercises in healthcare, thus making the 4th Industrial Revolution more relevant.

The Pathogen Whole-Genome Sequencing method has been one of the least expensive and fast genotypic techniques in disease surveillance. Essentially, this method is very effective in the "identification, accuracy, speed, antimicrobial resistance profiling, biological risk prediction, outbreak prediction, outbreak identification and pathogen tracking" (Hoelzer *et al.*, 2018; Gilbert *et al.*, 2019; Wheeler, 2019; Pinto *et al.*, 2022). This shows that automated data that are analysed, capacitates health officials to timeously detect, identify and observe disease timelines over time. This is an opportunity for more studies in machine-learning innovations that will inform public health interventions.

Routine health-information systems, as defined by Lebelo and Van Wyk (2019b), are ongoing collection and processing of data on a particular health event in an ongoing way. They further state that "in a country with significant" health concerns and limited resources, there is a need to understand the diseases responsible for the main burden on healthcare services. Authorities usually use statistical data to measure the impact of diseases on other health outcomes. The knowledge of the factors contributing to FBDs should be readily available to consumers and the food industry personnel (Wu *et al.*, 2018; Wu, Liu and Chen, 2018). This allows for timely responses in case of outbreaks and other related investigations. Food Safety Regulatory authorities must have access to outbreak data to improve the food supply system and institute appropriate control measures (Kendall *et al.*, 2018; Bouzembrak and Marvin, 2019; Aiyar and Pingali, 2020; Jin *et al.*, 2020). Figure 4.4 shows the challenges experienced by authorities in food control initiatives. These challenges stem from the lack of collaboration between related governmental departments and the food industry's growth trajectory. Further shortfalls include the lack of skill in inspection services and human resource capacity.

Figure 4.4: Key food control global challenges.

4.5. Food contamination in the value chain and economic loss

Food Food is an undeniable commodity, as shown in the amount of municipal solid waste. The solid waste generated by municipalities is largely attributed to food followed by plastics (Gu *et al.*, 2015). Moreover, factors such as urbanisation exacerbate the demand for food in industrialized regions and further impact human health (Oguntoyinbo, 2014; Leal Filho *et al.*, 2016; Pozio, 2020). This huge demand for food gives rise to potential hazards in the value chain. The World Health Organization (WHO) defines foodborne diseases as illnesses resulting from the ingestion of contaminated foodstuffs, and the contamination can be from environmental pollution caused by chemicals and microorganisms (Abdul Rasam and Mohd Noor, 2012). Foodborne outbreaks have been occurring for centuries and have continued to deplete health authorities' resources. Food handlers can spread the disease-causing agents passively from the contaminated source. Therefore, in addition to a medical examination of the affected individuals, most researchers recommend the implementation of training programmes in food safety to form a more comprehensive food control system (Manes, Liu and Dworkin, 2013; Basavegowda *et al.*, 2014; Djekic *et al.*, 2014a & 2014b; Gumbo *et al.*, 2015; Sim and Wiwanitkit, 2021).

Foodborne outbreaks come in different forms and magnitudes due to factor the type of food and how it was produced. In the past, nations focused on the quantity of food produced instead of the quality, thus neglecting resources that assist in food safety. Developing nations such as South Africa have come up with social impact initiatives such as the zero hunger programme for poverty alleviation in rural communities. It is still uncertain as to the extent of food safety since the primary goal is the quantity of the food (De Cock *et al.*, 2013; Massomo, 2020).

In the United States of America (USA), raw food or produce has been likened to outbreaks that transcend state borders, compared to other food categories (Bennett *et al.*, 2015). Fruits and vegetables are sensitive foods in that they potentially pose the greatest danger, although they are staples in a healthy diet (Mandizvidza, 2018). As a result, stringent measures must be instituted in the form of legislation in the USA. In 2015, standards were enacted to govern the production chain of produce for human consumption. These standards focused on microbial quality, employee hygiene and the quality of agricultural water. In South Africa, following the listeriosis outbreak in 2017, strengthened efforts were required from food processing plants to use deep-cleaning methods to eliminate the growth and survival of pathogens (Chersich *et al.*, 2018). Ultimately, the food industries and policymakers must find better strategies to conduct risk assessments (Tomno *et al.*, 2020) and use the available resources in dealing with foodborne illnesses (Hoffmann *et al.*, 2015; Draeger *et al.*, 2019).

It is widely understood that infections can also influence economic loss due to food industry operations being brought to a halt during outbreak investigations (Focker and Van der Fels-Klerx, 2020; Li *et al.*, 2020). This was evident in one of the largest listeriosis outbreaks in South Africa. According to Smith *et al.* (2019), a total of 1 060 cases were reported from the 1st of January 2017 to the 17th of July 2018. During this period, there were significant economic losses for both the implicated business and other businesses along the food supply chain (Thomas *et al.*, 2020); thus, the need for a constant surveillance and trend analysis. In a study by Hoffman and colleagues, the following factors were considered in measuring the economic burden of FBDs: cases that do not require medical care but were hospitalised; cases that required medical assistance but were not hospitalised; hospitalised cases of varying severity and deaths. These factors show that in all the stages of the illness there are cost implications in the form of hidden costs, whether the cases were hospitalised or not (Hoffmann *et al.*, 2015).

4.6. Climate change and the manifestation of foodborne diseases

The global temperature has led to a plethora of phenomena. The most notable is the concept of climate change. It is predicted that between 2016 and 2035, the global average surface temperature would have increased by a range of 0.3–0.7 °C and a further 0.3–4.8°C by the end of the 21st century (Hellberg and Chu, 2016). The effect of climate change is far-reaching, and humidity and temperature are known to affect the manifestation and growth of pathogens (Kim *et al.*, 2015; Hellberg and Chu, 2016; Lake and Barker, 2018; Park, Park and Bahk, 2018b; El-Sayed and Kamel, 2020). The optimal temperature for most foodborne bacterial pathogens is close to that of the human body (37 °C). Furthermore, growth is also dependent on osmotic pressure, competition of microorganisms, water content and nutrient availability (Hellberg and Chu, 2016). Researchers (Kim *et al.*, 2015; Hellberg and Chu, 2016; Park *et al.*, 2018b) have noted several factors that can be affected by climate change. These factors include rain patterns, atmospheric temperature, environmental conditions and acidification.

Climate change can have a snowball effect on the food production and supply chain from the farm to the consumer table. This is evident in countries that are affected by meteorological disasters. The disasters increase the probability of infection by contaminating water sources and food sources (Lal *et al.*, 2013; Na *et al.*, 2016; Smith and Fazil, 2019; González *et al.*, 2020; Padrón *et al.*, 2020). Na *et al.* (2016) further elucidate the effects of climatological disasters on public health through other quantitative assessments of the effects of greenhouse gases on climate change. In retrospect, this has been on the global agenda of sustainable development adopted by the United Nations.

Different researchers have demonstrated that climatic conditions affect specific pathogens differently, depending on the region and the type of pathogen (Selstad Utaaker and Robertson, 2015; Misiou and Koutsoumanis, 2021). This has led to the recommendation that more studies need to be conducted to measure the correlation between climate change and food safety and the consequential foodborne outbreaks (Kim *et al.*, 2015). This recommendation was later supported by researchers (Hellberg and Chu, 2016; Park *et al.*, 2018b), who suggested large-scale multiple climatic factors across wider regions. In their study in South Korea, Kim and colleagues collected secondary data on climatic conditions, and foodborne outbreaks from the Korean Ministry of Food and Drug Safety and the Korea Metrological Administration (Kim *et al.*, 2015). The study period was from 2003 to 2012 and it focused on the effect of relative humidity and temperature calculations concerning FBDs. Similarly, a study with similar metric measurements in New Zealand revealed that *Salmonella* spp and *Campylobacter* infections peak in the warmer and wetter summer months. Weisent *et al.* (2014) discovered that campylobacteriosis seasonal trends vary depending on the geographical area. Furthermore, *Campylobacter* spp are found naturally in the environment or food sources (Soneja *et al.*, 2016; Murray *et al.*, 2020). Therefore, it can be deduced that humans are at risk of exposure when outdoors in warmer months, where most of their leisure and recreational activities take place. *Salmonella* is primarily found in food sources; however, the increased enteric infections can also be attributed to contaminated water sources and other agricultural produce, including livestock (Lal *et al.*, 2013; Hellberg and Chu, 2016; Lake, 2017; Soltan Dallal *et al.*, 2020).

Accounting for variables such as temperatures and relative humidity is one way of assessing the potential contamination of food. This is in consideration of the adverse conditions that these climatic conditions can potentially cause. In recent years, the use of climate-based early warning systems has been considered in public health interventions, and it is believed that prediction models can be designed using historical patterns of climate-sensitive diseases (Lal *et al.*, 2013). Moreover, climate data are freely and readily available for public health officials for use in disease forecasting and generating baseline indices (Weisent *et al.*, 2014; Kim *et al.*, 2015; Chersich *et al.*, 2018; Park *et al.*, 2018b).

Researchers are trying to understand the phenomena of the interrelationships among foodborne pathogens and meteorological features. Microbial resistance and distribution in the outdoor environment are complex, due to different factors playing a significant role (Smith and Fazil, 2019). Hellberg and Chu (2016) list four fundamental factors that influence the dispersal and persistence of foodborne pathogens; firstly, the epidemiology of the pathogen in terms of how it is transmitted and how it spreads; secondly, the geography and natural features of the pathogens about the most favourable environments for growth; thirdly, the anthropogenic elements such as infrastructure; and lastly, the human behavioural patterns regarding food safety (Smith and Fazil, 2019) and food-handling practices. Public health interventions, with the inclusion of educational awareness campaigns on the effect of weather patterns on infectious diarrhoea, are perceived to be effective tools to reduce the risk of transmitting the disease (Wang *et al.*, 2019). Moreover, such interventions need to be integrated from different spheres of government and private institutions to be effective. However, researchers argue that the shift in weather patterns could make the enforcement of regulations and surveillance of infections insufficient (Lake, 2017; Smith and Fazil, 2019).

4.7. Global trends overview

A global review study (n = 2932) by Soon and co-workers investigating the common contributory factors in food safety incidents between 2008 and 2018 revealed that 69% of the total incidents were a result of microbiological cross-contamination and undeclared allergens (Soon *et al*., 2020). This study had four categories of analysis, namely biological, chemical, physical and allergens. A similar study on the Surveillance for Foodborne Disease Outbreaks in China from 2003 to 2008 showed a decrease in the outbreak rate (1.37 to 0.46 per 1 million population). Further results showed that 48% of the outbreaks were caused by bacteria; 25% by man-made chemicals; 25% by animal and plant toxins; and only one outbreak was caused by a virus. Despite the generally applaudable regulation of food chemical hazards in developed nations, the problem persists in China. Acute poisonings account for all cases in the outbreak. This shows the extent of the problems regarding the containment of outbreaks in China. Armaroli *et al.* (2020) propose that worldwide data can be collected in food databases and be used by developing nations in the identification of chemicals that are likely to contaminate food. This data will be collected to provide the statistical description and distribution. The information collected has been noted to offer benefits such as robust monitoring programmes and estimating the variability of contamination. Further opportunities in controlling chemical hazards include research, training and harmonizing food systems (Matouke and Abdullahi, 2020; Savelli *et al*., 2021) and supporting local agricultural services (Galagarza *et al*., 2021). Figure 4.5 shows the co-occurrence of keywords in food contamination and surveillance research. The sizes, notes and words as shown depict the weights of the notes. Keywords such as ‘food contamination’’ (315), food safety (238), ‘exposure’ (154), and ‘food contaminants’ (147) have bigger nodes, showing that they occur more frequently.

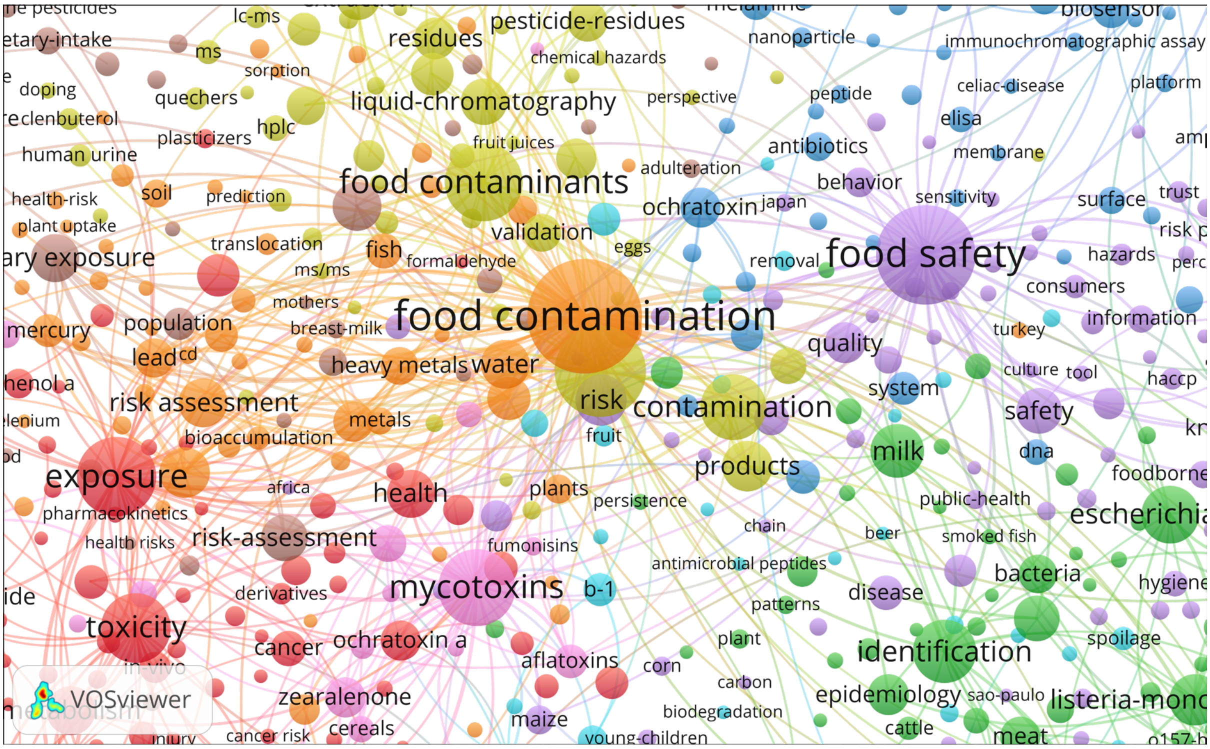

Figure 4.5: Bibliometric network visualization of the co-occurrence of keywords.

Most cases of diarrhoea are viral by nature, and global statistics show that the rotavirus and norovirus account for more infections of gastroenteritis outbreaks, especially in cold seasons (Wu *et al.*, 2018; Wang *et al.*, 2019). The authors further report that the surveillance data in China showed that 99.7% of laboratory-confirmed cases of infectious diarrhoeal cases were caused by the rotavirus and norovirus. Other studies in Africa have shown an increased incidence of diarrhoeal cases, following increased temperatures and heavy rainfall (Chaiphongpachara, 2019). Moreover, with the focus largely being on bacterial and parasitic infections, which are mainly transmitted through contaminated water and food, more research needs to be conducted on the association between meteorological factors and infectious diarrhoea (Chaiphongpachara, 2019). A study in South Korea has found a correlation between the incidences of 4 out of the 13 bacterial foodborne illnesses studied, based on the following factors: hospitalization and 8 climatic factors. In this study, the potential predictive factors for salmonellosis, vibriosis and Enterohemorrhagic *Escherichia coli* (EHEC) O157:H7 infection were temperatures, precipitation, cloudiness and relative humidity. It is important to understand the combined influence of climatic variation on the manifestation of FBDs. This will allow scientists to predict the regional incidence of pathogens and foodborne disease outbreaks (Park, Park and Bahk, 2018a).

Figure 4.6. shows the key research themes based on food contamination and surveillance research. The size of the circles is proportional to the number of publications equivalent to each keyword in each quadrant. The upper-right quadrant (motor theme) is characterised by high centrality and density. This quadrant presents developed, saturated and important themes (exposure, toxicity, *Escherichia coli*) in food contamination and research. The upper-left quadrant (niche/specialized theme) shows topics with high density but low centrality. This symbolises a stronger relationship with one another, but a weaker link to the keywords; thus, only marginally relevant to the field (nanoparticles and rapid detection). The lower-left quadrant (emerging or declining theme) specifies research studies that are weakly developed and marginal, with low centrality and low density (liquid chromatography, mass spectrometry, food products). Finally, the lower-right quadrant (basic theme) represents topics with high centrality but low density. These are important and concerning themes (contamination, growth, risk assessments, heavy metals) in this research field (Akter, Uddin and Tajuddin, 2021).

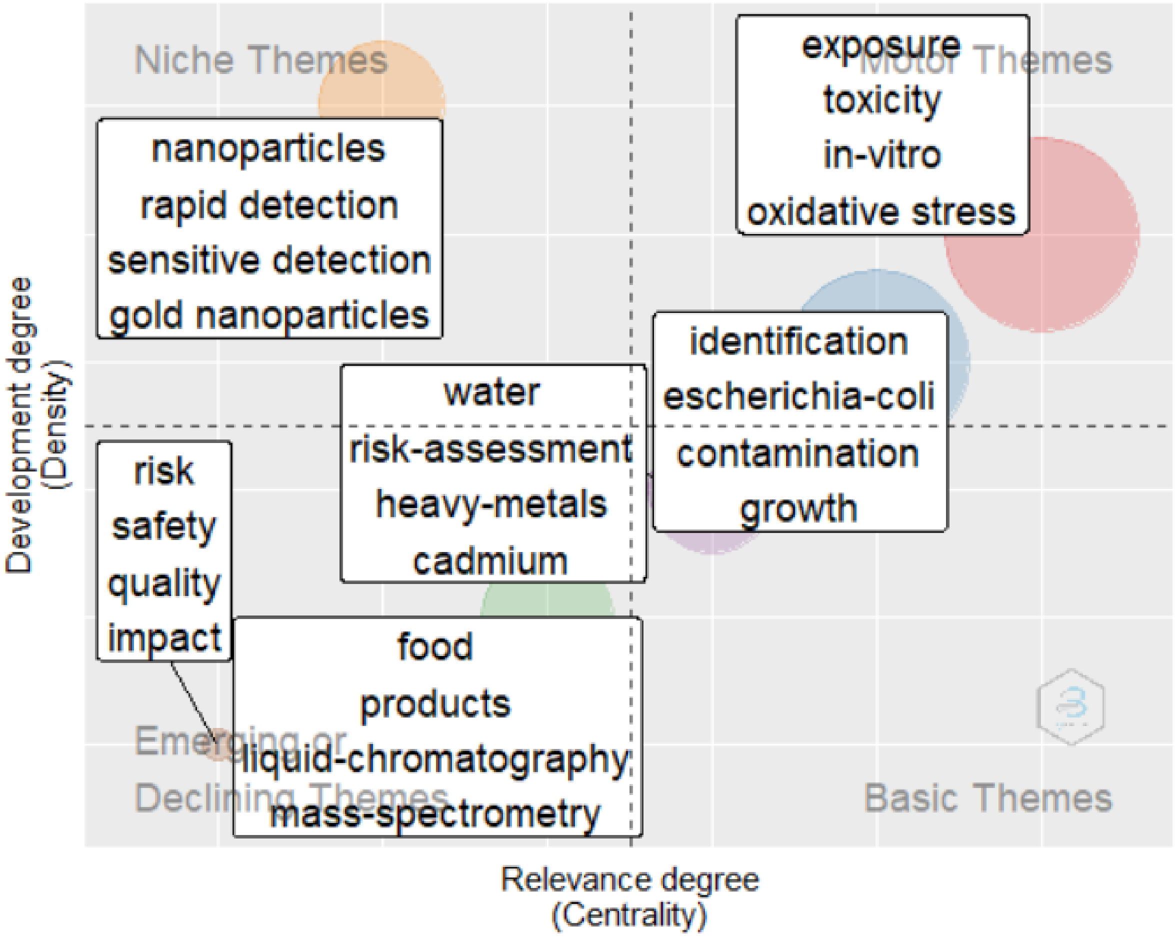

Figure 4.6: Thematic progression of food contamination and surveillance research (2011-2021).

4.8. The application of geographic information systems in surveillance

Different epidemiological studies have shown how diseases are distributed in regions, and further demonstrate the pattern of disease in certain geographic locations. A key aspect of geographical epidemiology is assessing the distribution of disease and death rates (Lee, 2017). Therefore, the usage of Geographic Information Systems (GISs) is an increasingly important area in descriptive epidemiology. The GIS essentially draws, edits and organizes data for optimal analysis and spatial distribution of geospatial data (Abdul Rasam and Mohd Noor, 2012; Lee, 2017; Chang, 2019). Disease mapping is a concept that has been applied for over a century but most studies focused on person, place and time when investigating outbreaks (Smith *et al.*, 2015). The authors found GISs very robust in examining the spatial distribution of diseases. Furthermore, these systems assist in planning health resources, identifying risk factors, the relative location of cases, improve infrastructure and policy implementation (Nadi *et al.*, 2016). Diseases can be mapped using incident rates and point sources. Maps can be a good method of transmitting information; however, for complex analysis of sophisticated relationships, it can be hard to arrive at the wrong conclusion regarding explanatory variables. This can lead to further misinterpretation due to colour map display, thus neglecting the fundamentals of data handling, analysis and presentation (Samarasundera *et al.*, 2012).

These tools have been reported to have the ability to handle vast volumes of data and rapidly compare with different sources (Kirby, Delmelle and Eberth, 2017). Moreover, the data derived from various sources can further be used for remote sensing to analyse a wide range of environmental exposure. Despite the considerable advantages, the maintenance of the system has been reported to be costly and requires a special skill set. The good news is that lately, the software is easy to learn. The hardware usually includes computers, a global positioning system (GPS), mobile devices and hardcopy maps (Chang, 2019).

In primary healthcare, GIS systems have gained ground in determining statistically significant clusters (hotspots) and outliers (cold spots) in service delivery and resource apportionment strategies (Samarasundera *et al.*, 2012; Smith *et al.*, 2015). Within the context of environmental health, the same can be used to determine where foodborne outbreaks occur and the kind of resources that will be needed to alleviate the problems. Services planning is essential for public health officials that deal with outbreaks. Distance and network routes must be analysed to provide efficient ways to arrive at the desired study location. This can be achieved through remote sensing, which is a technology placed on a platform used to collect data on the earth for inventory and monitoring (Abdul Rasam and Mohd Noor, 2012).

4.9. Big-data and intelligent systems approach

Researchers are in consensus that surveillance as a function is crucial in disease control and prevention. The current systems are viewed as "insensitive and slow" (Lee, 2017; Gilbert *et al.*, 2019). The authors further mention that big-data-based electronic surveillance systems by government agencies are of paramount importance and have thus gained recognition as an alternative for rapidly detecting disease outbreaks due to their customised and specialised algorithms. According to Gilbert *et al.* (2019), big data and data analytics have been explored in detail in various studies, where the former is defined as the large volumes of complex data and the acquisition thereof. Data analytics refers to the collection, organisation and analysis of larger datasets to discover patterns in the information for specific interventions (Collins and M Moons, 2019). Globally, big data is used everywhere by different organisations for improving service delivery (Indhumathi and Sathesh Kumar, 2020). Unofficial data can be randomly collected by conglomerates in retail, advertisers and even crime-prevention authorities in a quest to monitor behaviours and trends (Gilbert *et al.*, 2019; Velmovitsky *et al.*, 2021). In addition, surveillance has been existing for ages, though the recent advances in technology have transformed the accessibility and that enhances speedy data processing and analysis.

Big data mining is relatively new in healthcare service delivery, partially to the potential privacy issues and manual keeping of records. However, with the increase in scientific research, the digitisation of healthcare data has been on the rise (Song *et al.*, 2017; Bragazzi *et al.*, 2020; Jin *et al.*, 2020). This is observed in the improved administrative processes where laboratory results and various medical records are submitted through digital platforms (Gilbert *et al.*, 2019). Ideally, a single data repository containing personal health records from various agencies could benefit public health researchers and relevant authorities who have the authorisation to access such data (Jia *et al.*, 2020). In the same notion, a similar concept should be explored where a particular system can contain meteorological data, population and spacing, food industries, socio-economic factors, rural and urban classification systems, etc. Arguably, these systems will be prone to abuse and misuse of data, resulting in ethical issues and security issues. In addition, the benefits far outweigh the disadvantages from a scientific point of view.

However, enforcing the strictest technical standards can never fully guarantee data safety and security (Gilbert *et al.*, 2019).

Forecasting foodborne disease outbreaks is a multifaceted public health strategy with socio-economic benefits (Weiser *et al.*, 2016). In recent years, technologies have been proposed to investigate foodborne outbreaks. In a study by Weiser *et al.* (2016), a reconstruction network was reviewed regarding the analysis of the causes of foodborne outbreaks. In this study, an open-source software called FoodChain-Lab was used due to its ability to "trace back and trace forward" food items suspected to be problematic in the food supply chain. Essentially, this software can use the GIS system to generate locations of different stages in the food supply chain through graphic visualization. Furthermore, it can compute the tracing score to determine which stage in the chain has likely caused contamination. This tool has proven reliable in recent studies, and it can assist government departments in outbreak investigations related to food.

Foodborne diseases pose significant challenges at various levels of the government. A small portion of affected individuals seeks medical care upon showing preliminary clinical symptoms. In addition, from this small portion, only a fraction will be investigated according to the responsible hazards. Ultimately, only a few cases will get the relevant medical treatment and will be reported to public health authorities to eventually form part of official government statistics (Mehlhorn, 2015). This supports the notion of adopting a One Health Approach, which promotes interdisciplinary and intersectoral strategies of resource allocation to address health shortcomings (Lee, 2017).

Researchers studying the prediction of morbidity as a result of gastrointestinal infections caused by food contamination determined that deep-learning models have useful applications in surveillance (Song *et al.*, 2017). Song and co-worker's paper on deep de-noising auto-encoder (DDAE), a deep neural network (DNN) was constructed to predict the morbidity of gastrointestinal infections, due to contaminated food. The experiment showed that the developed evolutionary deep-learning model has more prediction accuracy than other methods such the artificial neural networks (ANNs) and DDAE. Furthermore, this deep-learning model could be applied in establishing prediction models, even when the data are incomplete. There are other applications of machine-learning algorithms. A paper by Gupta and Katarya (2020) highlights the powerful usage of social media and machine learning in syndromic surveillance. In their study, they note that the use of social media surveillance systems is superior compared to traditional systems. However, is it important to note that this surveillance method comes with challenges such as sifting through irrelevant data/news, data validation and the reliability of the data sources.

There are variations in predictive studies. The surge in FBDs has propelled organisations to come up with innovative strategies to rapidly detect and reduce food contamination by pathogens. Yousefi *et al.* (2018) have used DNAzyme-based sensing surfaces in their study and reported several advantages such as real-time detection of target bacteria, especially in packaged foods. Food contamination monitoring can be conducted via the internet of things. A study on food contamination monitoring was using a pocket-sized immunosensor system installed with a Wi-Fi module. This allowed the researchers to analyse foods and share the results through wireless networks. The same concept can also be applied to the surveillance and control of communicable diseases. Moreover, it can manage biosensing data derived from wearable devices on the body connected through the internet of things (Seo *et al.*, 2016).

4.10. Conclusion

In this paper, the author highlighted some of the key topics in food contamination and surveillance studies. Further, the implications of emerging trends were discussed to show the general progression of the research field. Foodborne diseases have been a burden to the global public health and surveillance system. This is evident in a positive upward research trend in food contamination and surveillance research in the last decade. Further, they influence economic loss due to increased medical expenses and potential disturbances in the food industry. Despite challenges such as underreporting and delays, surveillance and exposure assessments remain critical key performance indicators of effective and efficient public health systems. Food safety risks remain paramount in designing effective detection and surveillance systems. The globalisation of trade and environmental factors play a significant role in safeguarding against emerging and existing food safety risks in the food production chain until the consumer level.

This work has also provided context on the need for innovative studies in machine learning for predictive qualities in surveillance and improved digitized systems to inform public health interventions and policies. Limitations in this review include the fact that not all research papers added to the WoS are indexed in the core collections. In addition, the database may have erroneous data, thus increasing the likelihood of omission of some papers due to search queries. In future, a systematic approach with multiple databases will be employed for in-depth article content analysis in food contamination and surveillance research.

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4.11. References

Abdul Rasam, A. R. and Mohd Noor, A. M. (2012) 'Contribution of GIS and remote sensing technologies for managing foodborne diseases in Malaysia', *Proceedings – 2012 IEEE Control and System Graduate Research Colloquium, ICSGRC 2012*, (Icsgrc), pp. 258–261. doi: 10.1109/ICSGRC.2012.6287172.

Aiyar, A. and Pingali, P. (2020) 'Pandemics and food systems – towards a proactive food safety approach to disease prevention & management', *Food Security*, 12(4), pp. 749–756. doi: 10.1007/s12571-020-01074-3.

Akter, S., Uddin, M. H. and Tajuddin, A. H. (2021) 'Knowledge mapping of microfinance performance research: a bibliometric analysis', *International Journal of Social Economics*, 48(3), pp. 399–418. doi: 10.1108/IJSE-08-2020-0545.

Althouse, B. M. *et al.* (2015) 'Enhancing disease surveillance with novel data streams: challenges and opportunities', *EPJ Data Science*, 4(1), pp. 1–8. doi: 10.1140/epjds/s13688-015-0054-0.

Amene, E. *et al.* (2016) 'Variable selection and regression analysis for the prediction of mortality rates associated with foodborne diseases', *Epidemiology and Infection*, 144(9), pp. 1959–1973. doi: 10.1017/S0950268815003234.

Ankar-Brewoo, G. M. *et al.* (2020) 'Health risks of toxic metals (Al, Fe and Pb) in two common street vended foods, fufu and fried-rice, in Kumasi, Ghana', *Scientific African*, 7. doi: 10.1016/j.sciaf.2020.e00289.

Armaroli, E. *et al.* (2020) 'A method to prioritize the surveillance of chemicals in food commodities to access international market and its application to four countries in Sub-Saharan Africa', *Environment International*, 135, p. 105386. doi:

10.1016/j.envint.2019.105386.

Bai, S. H. and Ogbourne, S. M. (2016) ‘Glyphosate: environmental contamination, toxicity and potential risks to human health via food contamination’, *Environmental Science and Pollution Research*, 23(19), pp. 18988–19001. doi: 10.1007/s11356-016-7425-3.

Baquero, O. S., Santana, L. M. R. and Chiaravalloti-Neto, F. (2018) ‘Dengue forecasting in São Paulo city with generalized additive models, artificial neural networks and seasonal autoregressive integrated moving average models’, *PLoS ONE*, 13(4), pp. 1–12. doi: 10.1371/journal.pone.0195065.

Basavegowda, M. *et al.* (2014) ‘An outbreak of staphylococcal food poisoning in a nursing hostel, Mysore, Karnataka’, *International Journal of Medicine and Public Health*, 4(3), p. 257. doi: 10.4103/2230-8598.137712.

Benke, K. and Benke, G. (2018) ‘Artificial intelligence and big data in public health’, *International Journal of Environmental Research and Public Health*, 15(12). doi: 10.3390/ijerph15122796.

Bennett, S. D. *et al.* (2015) ‘Multistate foodborne disease outbreaks associated with raw tomatoes, United States, 1990-2010: A recurring public health problem’, *Epidemiology and Infection*, 143(7), pp. 1352–1359. doi: 10.1017/S0950268814002167.

Berking, C. *et al.* (2019) ‘Non-compliances - an indicator of food control effectiveness’, *Infection Ecology and Epidemiology*, 9(1). doi: 10.1080/20008686.2019.1599276.

Bouzembrak, Y. and Marvin, H. J. P. (2019) ‘Impact of drivers of change, including climatic factors, on the occurrence of chemical food safety hazards in fruits and vegetables: A Bayesian Network approach’, *Food Control*, 97, pp. 67–76. doi: 10.1016/j.foodcont.2018.10.021.

Bragazzi, N. L. *et al.* (2020) ‘How big data and artificial intelligence can help better manage the Covid-19 pandemic’, *International Journal of Environmental Research and Public Health*, 17(9), pp. 4–11. doi: 10.3390/ijerph17093176.

Camargo, A. C. *et al.* (2017) ‘Listeria monocytogenes in Food-Processing Facilities, Food

Contamination, and Human Listeriosis: The Brazilian Scenario', *Foodborne Pathogens and Disease*, 14(11), pp. 623–636. doi: 10.1089/fpd.2016.2274.

Chaiphongpachara, T. S. P. (2019) 'Risk Assessment of Diarrhoeal Disease Using a Geographic Information', *J. Biotechnol*, 16(1), pp. 35–39.

Chang, K. (2019) 'Geographic information system technology', *The International Encyclopedia of Geography*. John Wiley & Sons, Ltd. doi: 10.1002/9781118786352.wbieg0152.pub2.

Chersich, M. F. *et al.* (2018) 'How climate change can fuel listeriosis outbreaks in South Africa', *South African Medical Journal*, 108(6), pp. 453–454. doi: 10.7196/SAMJ.2018.v108i6.13274.

Clarke, M. F. *et al.* (2011) 'Direct and indirect impact on rotavirus positive and all-cause gastroenteritis hospitalisations in South Australian children following the introduction of rotavirus vaccination', *Vaccine*, 29(29–30), pp. 4663–4667. doi: 10.1016/j.vaccine.2011.04.109.

De Cock, N. *et al.* (2013) 'Food security in rural areas of Limpopo province, South Africa', *Food Security*, 5(2), pp. 269–282. doi: 10.1007/s12571-013-0247-y.

Collins, G. S. and M Moons, K. G. (2019) 'Reporting of artificial intelligence prediction models'. doi: 10.1016/S0140-6736(19)30235-1.

Convertino, M., Liu, Y. and Hwang, H. (2014) 'Optimal surveillance network design: a value of information model', *Complex Adaptive Systems Modeling*, 2(1), pp. 1–23. doi: 10.1186/s40294-014-0006-8.

De Cock, N. *et al.* (2013) 'Food security in rural areas of Limpopo province, South Africa', *Food Security*, 5(2), pp. 269–282. doi: 10.1007/s12571-013-0247-y.

Djekic, I., Smigic, N., Kalogianni, E. P., Rocha, A., Zamioudi, L. and Pacheco, R. (2014a) 'Food hygiene practices in different food establishments', *Food Control*, 39(1), pp. 34–40. doi: 10.1016/j.foodcont.2013.10.035.

Djekic, I., Smigic, N., Kalogianni, E. P., Rocha, A., Zamioudi, L., Pacheco, R. *et al.* (2014b) 'The role of theoretical food safety training on Brazilian food handlers' knowledge, attitude and practice', *Food Control*, 43(1), pp. 34–39. doi: 10.1016/j.foodcont.2013.10.035.

Draeger, C. L. *et al.* (2019) 'Brazilian foodborne disease national survey: Evaluating the landscape after 11 years of implementation to advance research, policy, and practice in public health', *Nutrients*, 11(1). doi: 10.3390/nu11010040.

Ebel, E. D. *et al.* (2016) 'Comparing characteristics of sporadic and outbreak-associated foodborne Illnesses, United States, 2004-2011', *Emerging Infectious Diseases*, 22(7), pp. 1193–1200. doi: 10.3201/eid2207.150833.

El-Sayed, A. and Kamel, M. (2020) 'Climatic changes and their role in emergence and re-emergence of diseases', *Environmental Science and Pollution Research*, 27(18), pp. 22336–22352. doi: 10.1007/s11356-020-08896-w.

Faour-Klingbeil, D. and Todd, E. C. D. (2020) 'Prevention and control of foodborne diseases in middle-east north african countries: Review of national control systems', *International Journal of Environmental Research and Public Health*, 17(1), pp. 1–23. doi: 10.3390/ijerph17010070.

Focker, M. and van der Fels-Klerx, H. J. (2020) 'Economics applied to food safety', *Current Opinion in Food Science*, 36, pp. 18–23. doi: 10.1016/j.cofs.2020.10.018.

Galagarza, O. A. *et al.* (2021) 'Occurrence of Chemical Contaminants in Peruvian Produce : A Food-Safety Perspective', pp. 1–21.

Gilbert, G. L., Degeling, C. and Johnson, J. (2019) 'Communicable Disease Surveillance Ethics in the Age of Big Data and New Technology', *Asian Bioethics Review*, 11(2), pp. 173–187. doi: 10.1007/s41649-019-00087-1.

González, N. *et al.* (2020) 'Meat consumption: Which are the current global risks? A review of recent (2010–2020) evidences', *Food Research International*, 137 (April), p. 109341. doi: 10.1016/j.foodres.2020.109341.

Gould, L. H. *et al.* (2013) 'Surveillance for Foodborne Disease Outbreaks — United States, 1998–2008', 62(2), pp. 1–34. doi: 10.2307/24806072.

Gu, B. *et al.* (2015) 'Characterization, quantification and management of household solid waste: A case study in China', *Resources, Conservation and Recycling*, 98, pp. 67–75. doi: 10.1016/j.resconrec.2015.03.001.

Gumbo, A. *et al.* (2015) 'Staphylococcus aureus food poisoning among Bulawayo City Council employees, Zimbabwe, 2014', *BMC Research Notes*, 8(1), pp. 1–7. doi: 10.1186/s13104-015-1490-4.

Gupta, A. and Katarya, R. (2020) 'Social media based surveillance systems for healthcare using machine learning: A systematic review', *Journal of Biomedical Informatics*, 108 (April 2019), p. 103500. doi: 10.1016/j.jbi.2020.103500.

Havelaar, A. H. *et al.* (2015) 'World Health Organization Global Estimates and Regional Comparisons of the Burden of Foodborne Disease in 2010', *PLoS Medicine*, 12(12), pp. 1–24. doi: 10.1371/journal.pmed.1001923.

Hellberg, R. S. and Chu, E. (2016) 'Effects of climate change on the persistence and dispersal of foodborne bacterial pathogens in the outdoor environment: A review', *Critical Reviews in Microbiology*, 42(4), pp. 548–572. doi: 10.3109/1040841X.2014.972335.

Hoelzer, K. *et al.* (2018) 'Emerging needs and opportunities in foodborne disease detection and prevention: From tools to people', *Food Microbiology*, 75, pp. 65–71. doi: 10.1016/j.fm.2017.07.006.

Hoffmann, S., Maculloch, B. and Batz, M. (2015) 'Economic burden of major foodborne illnesses acquired in the United States', *Economic Cost of Foodborne Illnesses in the United States*, (140), pp. 1–74.

Indhumathi, K. and Sathesh Kumar, K. (2020) 'A review on prediction of seasonal diseases based on climate change using big data', *Materials Today: Proceedings*, 37 (Part 2), pp. 2648–2652. doi: 10.1016/j.matpr.2020.08.517.

Jansen, T. *et al.* (2020) '"All chemical substances are harmful." public appraisal of uncertain risks of food additives and contaminants', *Food and Chemical Toxicology*, 136(October 2019), p. 110959. doi: 10.1016/j.fct.2019.110959.

Jia, Q. *et al.* (2020) 'Big data analytics in the fight against major public health incidents (Including COVID-19): A conceptual framework', *International Journal of*

Environmental Research and Public Health, 17(17), pp. 1–21. doi: 10.3390/ijerph17176161.

Jin, C. *et al.* (2020) 'Big Data in food safety- A review', *Current Opinion in Food Science*, 36, pp. 24–32. doi: 10.1016/j.cofs.2020.11.006.

Kabanda, S. and Rother, H. A. (2019) 'Evaluating a South African mobile application for healthcare professionals to improve diagnosis and notification of pesticide poisonings', *BMC Medical Informatics and Decision Making*, 19(1). doi: 10.1186/s12911-019-0791-2.

Kendall, H. *et al.* (2018) 'Drivers of existing and emerging food safety risks: Expert opinion regarding multiple impacts', *Food Control*, 90, pp. 440–458. doi: 10.1016/j.foodcont.2018.02.018.

Khoury, M. J. *et al.* (2020) 'The intersection of genomics and big data with public health: Opportunities for precision public health', *PLoS Medicine*, 17(10), pp. 1–14. doi: 10.1371/journal.pmed.1003373.

Kim, Y. S. *et al.* (2015) 'Correlations between climatic conditions and foodborne disease', *Food Research International*, 68, pp. 24–30. doi: 10.1016/j.foodres.2014.03.023.

Kirby, R. S., Delmelle, E. and Eberth, J. M. (2017) 'Advances in spatial epidemiology and geographic information systems', *Annals of Epidemiology*, 27(1), pp. 1–9. doi: 10.1016/j.annepidem.2016.12.001.

Lake, I. R. (2017) 'Food-borne disease and climate change in the United Kingdom', *Environmental Health: A Global Access Science Source*, 16 (Suppl 1), pp. 53–59. doi: 10.1186/s12940-017-0327-0.

Lake, I. R. and Barker, G. C. (2018) 'Climate Change, Foodborne Pathogens and Illness in Higher-Income Countries', *Current environmental health reports*, 5(1), pp. 187–196. doi: 10.1007/s40572-018-0189-9.

Lal, A. *et al.* (2013) 'Climate variability, weather and enteric disease incidence in New Zealand: Time series analysis', *PLoS ONE*, 8(12), pp. 1–11. doi: 10.1371/journal.pone.0083484.

Leal Filho, W. *et al.* (2016) 'Benchmarking approaches and methods in the field of urban waste management', *Journal of Cleaner Production*, 112, pp. 4377–4386. doi: 10.1016/j.jclepro.2015.09.065.

Lebelo, K. *et al.* (2021) 'Chemical Contamination Pathways and the Food Safety Implications along the Various Stages of Food Production : A Review', *International Journal of Environmental Research and Public Health*, 18(11). doi: https://doi.org/10.3390/ijerph18115795.

Lebelo, K. and van Wyk, R. (2019a) 'Communicable disease Surveillance in the City of Ekurhuleni: Environmental Health Practitioners' perceptions', in *2019 Open Innovations Conference*, pp. 371–376. doi: 10.1109/OI.2019.8908191.

Lebelo, K. and van Wyk, R. (2019b) 'Knowledge and practices of Environmental Health Practitioners in communicable disease surveillance: City of Ekurhuleni', in *2019 Open Innovations Conference, OI 2019*, pp. 226–233. doi: 10.1109/OI.2019.8908262.

Lee, B. (2017) 'Foodborne disease and the need for greater foodborne disease surveillance in the Caribbean', *Veterinary Sciences*, 4(3). doi: 10.3390/vetsci4030040.

Li, K., Rollins, J. and Yan, E. (2018) 'Web of Science use in published research and review papers 1997–2017: a selective, dynamic, cross-domain, content-based analysis', *Scientometrics*, 115(1), pp. 1–20. doi: 10.1007/s11192-017-2622-5.

Li, W. *et al.* (2018) 'National molecular tracing network for foodborne disease surveillance in China', *Food Control*, 88, pp. 28–32. doi: 10.1016/j.foodcont.2017.12.032.

Li, W. *et al.* (2020) 'Surveillance of foodborne disease outbreaks in China, 2003–2017', *Food Control*, 118, p. 107359. doi: 10.1016/j.foodcont.2020.107359.

Mandizvidza, K. (2018) 'Vertical price linkages in food markets: Evidence from the tomato value chain of Northern South Africa', *Future of Food: Journal on Food, Agriculture and Society*, 6(1), pp. 30–39.

Manes, M. R., Liu, L. C. and Dworkin, M. S. (2013) 'Baseline knowledge survey of restaurant food handlers in Suburban Chicago: Do restaurant food handlers know what they need to know to keep consumers safe?', *Journal of Environmental Health*, 76(1), pp. 18–26.

Massomo, S. M. S. (2020) 'Aspergillus flavus and aflatoxin contamination in the maize value chain and what needs to be done in Tanzania', *Scientific African*, 10, p. e00606. doi: 10.1016/j.sciaf.2020.e00606.

Matouke, M. M. and Abdullahi, K. L. (2020) 'Assessment of heavy metals contamination and human health risk in *Clarias gariepinus* [Burchell, 1822] collected from Jabi Lake, Abuja, Nigeria', *Scientific African*, 7, p. e00292. doi: 10.1016/j.sciaf.2020.e00292.

Mayet, A. *et al.* (2011) 'Epidemiology of food-borne disease outbreaks in the French armed forces: A review of investigations conducted from 1999 to 2009', *Journal of Infection*, 63(5), pp. 370–374. doi: 10.1016/j.jinf.2011.08.003.

Mehlhorn, H. (2015) 'Food-Borne Disease Burden Epidemiology Reference Group', *Encyclopedia of Parasitology*, 51(4), pp. 1–1. doi: 10.1007/978-3-642-27769-6_3884-1.

Misiou, O. and Koutsoumanis, K. (2021) 'Climate change and its implications for food safety and spoilage', *Trends in Food Science and Technology*. doi: 10.1016/j.tifs.2021.03.031.

Murray, R. T. *et al.* (2020) 'Association between private drinking water wells and the incidence of Campylobacteriosis in Maryland: An ecological analysis using Foodborne Diseases Active Surveillance Network (FoodNet) data (2007–2016)', *Environmental Research*, 188(March), p. 109773. doi: 10.1016/j.envres.2020.109773.

Na, W. *et al.* (2016) 'Incidences of Waterborne and Foodborne Diseases After Meteorologic Disasters in South Korea', *Annals of Global Health*, 82(5), pp. 848–857. doi: 10.1016/j.aogh.2016.10.007.

Nadi, A. *et al.* (2016) 'Epidemiologic Investigation of Dysentery in North of Iran: Use of Geographic Information System (GIS)', *Materia Socio Medica*, 28(6), p. 444. doi: 10.5455/msm.2016.28.444-448.

Nayak, R. and Waterson, P. (2019) 'Global food safety as a complex adaptive system: Key concepts and future prospects', *Trends in Food Science and Technology*, 91(July), pp.

409–425. doi: 10.1016/j.tifs.2019.07.040.

Nerín, C., Aznar, M. and Carrizo, D. (2016) ‘Food contamination during food process’, *Trends in Food Science and Technology*, 48, pp. 63–68. doi: 10.1016/j.tifs.2015.12.004.

Nnebue, C. *et al.* (2012) ‘Awareness and knowledge of disease surveillance and notification by health-care workers and availability of facility records in Anambra state, Nigeria’, *Nigerian Medical Journal*, 53(4), p. 220. doi: 10.4103/0300-1652.107557.

Oguntoyinbo, F. A. (2014) ‘Safety Challenges Associated with Traditional Foods of West Africa’, *Food Reviews International*, 30(4), pp. 338–358. doi: 10.1080/87559129.2014.940086.

Osei-Tutu, B. and Anto, F. (2016) ‘Trends of reported foodborne diseases at the Ridge Hospital, Accra, Ghana: A retrospective review of routine data from 2009-2013’, *BMC Infectious Diseases*, 16(1). doi: 10.1186/s12879-016-1472-8.

Padrón, P. *et al.* (2020) ‘Trace Element Levels in Vegetable Sausages and Burgers Determined by ICP-OES’, *Biological Trace Element Research*, 194(2), pp. 616–626. doi: 10.1007/s12011-019-01778-4.

Pandey, A. *et al.* (2018) ‘Nature based solutions for contaminated land remediation and brownfield redevelopment in cities: A review’, *Bioresource Technology*, 74(1), pp. 1–13. doi: 10.1016/j.biortech.2018.01.003.

Park, M. S., Park, K. H. and Bahk, G. J. (2018a) ‘Combined influence of multiple climatic factors on the incidence of bacterial foodborne diseases’, *Science of the Total Environment*, 610–611, pp. 10–16. doi: 10.1016/j.scitotenv.2017.08.045.

Park, M. S., Park, K. H. and Bahk, G. J. (2018b) ‘Interrelationships between multiple climatic factors and incidence of foodborne diseases’, *International Journal of Environmental Research and Public Health*, 15(11). doi: 10.3390/ijerph15112482.

Pinto, R. B. *et al.* (2022) ‘Sensitivity of nutritional and microbial content of food wastes to drying technologies’, *Scientific African*, 16, p. e01130. doi: 10.1016/j.sciaf.2022.e01130.

Pozio, E. (2020) ‘How globalization and climate change could affect foodborne parasites’, *Experimental Parasitology*, 208, p. 107807. doi: 10.1016/j.exppara.2019.107807.

Ramirez-Hernandez, A. *et al.* (2020) ‘Food safety in Peru: A review of fresh produce production and challenges in the public health system’, *Comprehensive Reviews in Food Science and Food Safety*, 19(6), pp. 3323–3342. doi: 10.1111/1541-4337.12647.

Samarasundera, E. *et al.* (2012) ‘Methods and tools for geographical mapping and analysis in primary health care.’, *Primary health care research & development*, 13(1), pp. 10–21. doi: 10.1017/S1463423611000417.

Savelli, C. J. *et al.* (2021) ‘The utilisation of tools to facilitate cross-border communication during international food safety events, 1995–2020: a realist synthesis’, *Globalization and Health*, 17(1), p. 65. Available at: https://globalizationandhealth.biomedcentral.com/articles/10.1186/s12992-021-00715-2.

Secinaro, S. and Calandra, D. (2021) ‘Halal food: structured literature review and research agenda’, *British Food Journal*, 123(1), pp. 225–243. doi: 10.1108/BFJ-03-2020-0234.

Selstad Utaaker, K. and Robertson, L. J. (2015) ‘Climate change and foodborne transmission of parasites: A consideration of possible interactions and impacts for selected parasites’, *Food Research International*, 68, pp. 16–23. doi: 10.1016/j.foodres.2014.06.051.

Seo, S. M. *et al.* (2016) ‘Food contamination monitoring via internet of things, exemplified by using pocket-sized immunosensor as terminal unit’, *Sensors and Actuators, B: Chemical*, 233, pp. 148–156. doi: 10.1016/j.snb.2016.04.061.

Shonhiwa, A. M. *et al.* (2019) ‘A review of foodborne diseases outbreaks reported to the outbreak response unit, national institute for communicable diseases, South Africa, 2013–2017’, *International Journal of Infectious Diseases*, 79, p. 73. doi: 10.1016/j.ijid.2018.11.186.

Sim, S. and Wiwanitkit, V. (2021) ‘Food contamination, food safety and COVID-19 outbreak’, *Journal of Health Research*, (ahead-of-print), pp. 10–13. doi: 0.1108/jhr-01-2021-0014.

Simonsen, L. *et al.* (2016) 'Infectious disease surveillance in the big data era: Towards faster and locally relevant systems', *Journal of Infectious Diseases*, 214 (Suppl 4), pp. S380–S385. doi: 10.1093/infdis/jiw376.

Smith, A. M. *et al.* (2019) 'Outbreak of Listeria monocytogenes in South Africa, 2017-2018: Laboratory Activities and Experiences Associated with Whole-Genome Sequencing Analysis of Isolates', *Foodborne Pathogens and Disease*, 16(7), pp. 524–530. doi: 10.1089/fpd.2018.2586.

Smith, B. and Fazil, A. (2019) 'How will climate change impact microbial foodborne disease in Canada?', *Canada Communicable Disease Report*, 45(4), pp. 108–113. doi: 10.14745/ccdr.v45i04a05.

Smith, C. *et al.* (2015) 'Spatial methods for infectious disease outbreak investigations: Systematic literature review', *Euro Surveill.*, 20(39), pp. 1–21. Available at: www.eurosurveillance.org.

Soltan Dallal, M. M. *et al.* (2020) 'Associations between climatic parameters and the human salmonellosis in Yazd province, Iran', *Environmental Research*, 187 (May), p. 109706. doi: 10.1016/j.envres.2020.109706.

Soneja, S. *et al.* (2016) 'Extreme precipitation events and increased risk of campylobacteriosis in Maryland, U.S.A', *Environmental Research*, 149, pp. 216–221. doi: 10.1016/j.envres.2016.05.021.

Song, Q. *et al.* (2017) 'An evolutionary deep neural network for predicting morbidity of gastrointestinal infections by food contamination', *Neurocomputing*, 226 (November 2016), pp. 16–22. doi: 10.1016/j.neucom.2016.11.018.

Soon, J. M., Brazier, A. K. M. and Wallace, C. A. (2020) 'Determining common contributory factors in food safety incidents – A review of global outbreaks and recalls 2008–2018', *Trends in Food Science and Technology*, 97, pp. 76–87. doi: 10.1016/j.tifs.2019.12.030.

Tchatchouang, C. D. K. *et al.* (2020) 'Listeriosis outbreak in south africa: A comparative analysis with previously reported cases worldwide', *Microorganisms*, 8(1). doi: 10.3390/microorganisms8010135.

Thevis, M. *et al.* (2013) ‘Does the analysis of the enantiomeric composition of clenbuterol in human urine enable the differentiation of illicit clenbuterol administration from food contamination in sports drug testing?’, *Rapid Communications in Mass Spectrometry*, 27(4), pp. 507–512. doi: 10.1002/rcm.6485.

Thomas, J. *et al.* (2020) ‘Outbreak of listeriosis in South Africa associated with processed meat’, *New England Journal of Medicine*, 382(7), pp. 632–643. doi: 10.1056/NEJMoa1907462.

Tomno, R. M. *et al.* (2020) ‘Heavy metal contamination of water, soil and vegetables in urban streams in Machakos municipality, Kenya’, *Scientific African*, 9, p. e00539. doi: 10.1016/j.sciaf.2020.e00539.

Tong, P. and Song, Z. (2021) ‘Knowledge Mapping of Government Trust and Social Media Research: A Visual Analysis Using CiteSpace’, *Journal of the Australian Library and Information Association*, 70(2), pp. 139–156. doi: 10.1080/24750158.2020.1821321.

Velmovitsky, P. E. *et al.* (2021) ‘Convergence of Precision Medicine and Public Health Into Precision Public Health: Toward a Big Data Perspective’, *Frontiers in Public Health*, 9(April), pp. 1–17. doi: 10.3389/fpubh.2021.561873.

Wang, H. *et al.* (2019) ‘Association of meteorological factors with infectious diarrhea incidence in Guangzhou, southern China: A time-series study (2006–2017)’, *Science of the Total Environment*, 672, pp. 7–15. doi: 10.1016/j.scitotenv.2019.03.330.

Wang, J. *et al.* (2017) ‘A remote sensing data based artificial neural network approach for predicting climate-sensitive infectious disease outbreaks: A case study of human brucellosis’, *Remote Sensing*, 9(10). doi: 10.3390/rs9101018.

Wang, X. *et al.* (2018) ‘A Bayesian approach to real-time monitoring and forecasting of Chinese foodborne diseases’, *International Journal of Environmental Research and Public Health*, 15(8). doi: 10.3390/ijerph15081740.

Weisent, J. *et al.* (2014) ‘The importance of climatic factors and outliers in predicting regional monthly campylobacteriosis risk in Georgia, USA’, *International Journal of Biometeorology*, 58(9), pp. 1865–1878. doi: 10.1007/s00484-014-0788-6.

Weiser, A. A. *et al.* (2016) 'FoodChain-lab: Tracing Software Supporting Foodborne Disease Outbreak Investigations', *Procedia Food Science*, 7, pp. 101–104. doi: 10.1016/j.profoo.2016.02.097.

Wheeler, N. E. (2019) 'Tracing outbreaks with machine learning', *Nature Reviews Microbiology*, 17(5), p. 269. doi: 10.1038/s41579-019-0153-1.

WHO (2015) 'Food-Borne Disease Burden Epidemiology Reference Group', *Encyclopedia of Parasitology*. doi: 10.1007/978-3-642-27769-6_3884-1.

Wu, Y. ning *et al.* (2018) 'Surveillance for foodborne disease outbreaks in China, 2003 to 2008', *Food Control*, 84, pp. 382–388. doi: 10.1016/j.foodcont.2017.08.010.

Wu, Y. ning, Liu, P. and Chen, J. shi (2018) 'Food safety risk assessment in China: Past, present and future', *Food Control*, 90, pp. 212–221. doi: 10.1016/j.foodcont.2018.02.049.

Yang, W., Zhang, J. and Ma, R. (2020) 'The prediction of infectious diseases: A bibliometric analysis', *International Journal of Environmental Research and Public Health*, 17(17), pp. 1–19. doi: 10.3390/ijerph17176218.

Yousefi, H. *et al.* (2018) 'Sentinel Wraps: Real-Time Monitoring of Food Contamination by Printing DNAzyme Probes on Food Packaging', *ACS Nano*, 12(4), pp. 3287–3294. doi: 10.1021/acsnano.7b08010.

CHAPTER 5: CHEMICAL CONTAMINATION PATHWAYS AND THE FOOD SAFETY IMPLICATIONS ALONG THE VARIOUS STAGES OF FOOD PRODUCTION: A REVIEW

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Abstract

Historically, chemicals exceeding maximum allowable exposure levels have been disastrous to underdeveloped countries. The global food industry is primarily affected by toxic chemical substances because of natural and anthropogenic factors. Food safety is therefore threatened due to chemical contamination at various stages of food production. Persistent Organic Pollutants (POPs) in the form of pesticides and other chemical substances such as Polychlorinated Biphenyls (PCBs) have a widely documented negative impact due to their long-lasting effect on the environment. This review focuses on the chemical contamination pathways along the various stages of food production until the food reaches the consumer. The contamination of food can stem from various sources such as the agricultural sector and pollution from industrialized regions through the air, water, and soil. Therefore, it is imperative to control the application of chemicals during food packaging, and the application of pesticides and antibiotics in the food industry to prevent undesired residues in foodstuffs. Ultimately, the protection of consumers from food-related chemical toxicity depends on stringent efforts from regulatory authorities both in developed and underdeveloped nations.

Keywords: food safety; heavy metals; persistent organic pollutants; regulatory strategies

5.1. Introduction

Food control is a function carried out globally due to its public health importance. However, efforts in the enforcement and implementation of legislation regarding international codes and standards remain a challenge (Ahmad *et al.*, 2019; Aiyar and Pingali, 2020; Vipham *et al.*, 2020). This challenge is further exacerbated by the ever-rising human population, which is estimated to reach nine billion by the year 2050, thus creating a demand for increased food production (Yu *et al.*, 2020). The mass production of food and high demand contribute significantly to non-conformance to best practices and legal requirements. As a result, food control is prominent and various strategies are devised to alleviate the impact of non-compliance. Analytical tools for food control have been developed over the years; however, research suggests that none of these tools provides an exclusive and unique solution to food safety (Nerín, Aznar and Carrizo, 2016; Ahmad *et al.*, 2019). Some organizations have established early warning analytical systems to detect food safety risks on time and to improve the efficacy of surveillance in the food industry (Niu *et al.*, 2021). The beginning of the food production chain provides various food safety challenges. In food processing, chemicals may already be present in raw food. This happens due to advances in food science and the continued use of agrochemicals. The use of pesticides and fertilizers increases the risk of food contamination significantly (Bhalla *et al.*, 2019), and this risk is observed predominantly in food industries. Agricultural land situated in the vicinity of heavy industries can introduce contamination through the water, soil and air. This can ultimately cause a double burden of contamination due to the cumulative effect of agrochemicals and industrial pollutants (Bhalla *et al.*, 2019; Mandlate *et al.*, 2020). Possible contamination from toxic natural and industrial pollutants can be tested using a variety of techniques in the food industry. The major techniques with multi-element capability in the determination of contaminants are inductively coupled plasma atomic-emission spectrometry (ICP-OES) and graphite furnace atomic-absorption spectrometry (Mandlate *et al.*, 2020; Shariatifar *et al.*, 2020; Hossain *et al.*, 2021), inductively-coupled plasma mass spectrometry, flame atomic-absorption spectrometry, and cold-vapour, atomic-absorption spectrometry (Nerín *et al.,* 2016).

In a quest to promote the safety of food globally, regulatory bodies have advocated the declaration of food ingredients and contents through labelling and responsible marketing. This is in line with global trade markets and transparency (My, Demont and Verbeke, 2021). A challenge of note is that national regulations and guidelines do not always make provision for all chemical contaminant thresholds. This is because other chemical substances are legal in one country but prohibited in other parts of the world. According to Ahmad and co-workers, it is advisable to create a global agro-business chemical control programme to ensure regulatory compliance (Ahmad *et al.*, 2019). This will ensure that participating nations understand the chemical safety standards expected in the international food trade. Moreover, this comes with benefits such as consumer confidence, as stipulated in the *Codex Alimentarius*. This review paper provides an international view of current trends in food contaminants and how they impact the environment and human health. It further focuses on the chemical contamination pathways along the various stages of food production until the food reaches the consumer.

5.2. Food contamination along the food production chain

Food contaminants of chemical nature can be typically classified into four categories, namely natural toxins, environmental contaminants, agrochemical residues and food process toxicants, together with intentionally added chemicals (Oliver *et al.*, 2015; Rather *et al.*, 2017; Ahmad *et al.*, 2019; Thakali and MacRae, 2021). Therefore, the food production chain poses an intrinsic and extrinsic risk of contamination (Tempelhoff, 2009; Ng and Von Goetz, 2017). As shown in Figure 5.1, there are various levels of food production, and each stage has points where contamination can be introduced. The classifications of food contamination points are summarized below:

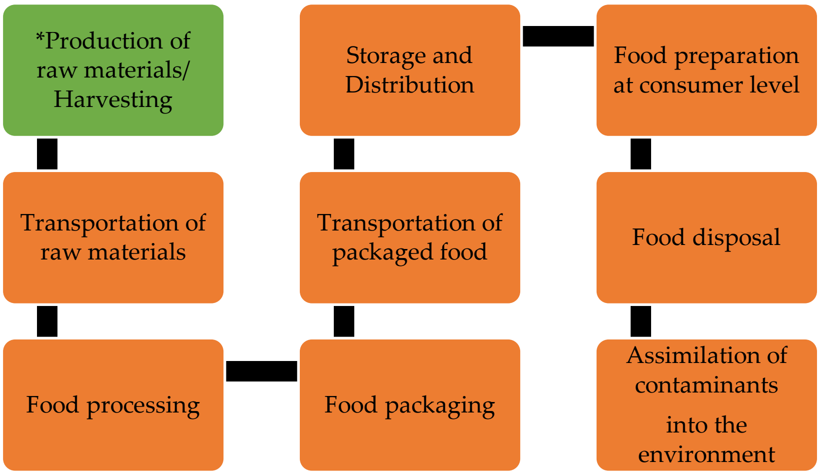

Figure 5.1: Key steps in food production, processing (farm-to-fork) till disposal. The figure is produced by the authors.

5.2.1. Transportation

Food can be contaminated during transportation as a result of both diesel and petrol engine vehicles, through exhaust systems that emit excessive carbon monoxide. In developing countries, transportation systems and logistics management systems are not as efficient regarding the shortening of distances when transporting food (Wang *et al.*, 2019). This increases the likelihood of unwanted substances settling on the foodstuffs. The contaminants can settle on the packaging material or directly on the food. The most commonly checked gases for permeation on packaging material are oxygen, carbon dioxide and water vapour. Therefore, other undetected compounds may infiltrate the barriers in the packaging (Nerín *et al.*, 2016). Moreover, not all barriers applied to foodstuffs are effective against organic compounds. Increased efforts are encouraged during the transportation process to limit food contamination exposure levels.

5.2.2. Cleaning agents

Cleaning agents in the food industry play a pivotal role in food safety. There are compounds such as peracetic acid, hydrogen peroxide and sodium hypochlorite, which are recommended for in deep cleaning in the food industry (Bernardi, Garcia and Copetti, 2019; Ortiz-Solà *et al.*, 2020). Disinfectants and most cleaning agents contain harmful compounds that have a pungent smell and corrosive properties. Notwithstanding their role in the deep cleaning of surfaces and the environment at large, they can easily be introduced into food through mishandling and unsafe practices, leading to residual toxicity (Marriott, Schilling and Gravani, 2018; Bernardi *et al.*, 2019). Heavy industrial chemicals need to be approved and regulated. Further, the chemical handlers must be provided with a material safety data sheet. International bodies such as the *Codex Alimentarius* and the United States Food and Drug Administration have introduced standards to alleviate the chances of food contamination through cleaning agents. These standards are voluntary but relevant, especially if companies want to trade internationally. Some compounds, when not properly diluted, cause adverse human health effects such as chronic dermatitis upon direct contact or prolonged use (Marriott *et al.*, 2018). This could be poisonous when introduced directly into food (Khare, Tonk and Rawat, 2018; Mohammadzadeh-Aghdash *et al.*, 2018; Sharif, Javed and Nasir, 2018). An array of products have been endorsed and others were discontinued due to their toxic effects on humans and the potential margin of damage in the event of food contamination. Historically, peroxides and most ammonium products are universally accepted within the specified scope of use and safety thresholds. Therefore, research must be conducted to determine the safety threshold of most cleaning agents in the food industry.

5.2.3. Food additives

Advancement in research in the food industry has been rapid and certain technologies have been introduced to counter food perishability and reduce the amount of food wasted due to microbial degradation. However, these technologies need to be introduced and used judiciously because of their potential to cause food-related illnesses (Hamid *et al.*, 2012; Faustino *et al.*, 2019; Jayant and Halami, 2020). Food additives represent some of the innovations introduced in the food industry to alleviate waste and prolong the shelf life of foodstuffs (Kamal and Fawzia, 2018; Roca-Saavedra *et al.*, 2018; Szűcs *et al.*, 2019). It is estimated that each person may consume close to 3.6 to 4.5 kg of food additives on average per annum (Bruna, Thais and Lígia, 2018). Food additives are described as "substances of natural or synthetic origin, which are added to foods to serve a technological or sensory function" (Pasca *et al.*, 2014). The definition is further expanded and described by the *Codex Alimentarius* as any substance that is not normally consumed as food but is used as a typical ingredient of the food to serve the purpose of adding nutritive value (Bruna *et al.*, 2018; Martins, Sentanin and De Souza, 2019). Furthermore, the addition of the substance will directly or indirectly be a component of the food. As shown in Figure 5.2, the synthetic materials in food can be categorized into different sub-categories according to their function in the food, i.e., colourants, emulsifying salts, flavour enhancers, acids, packaging gases, sweeteners, thickeners, etc. Moreover, food additives can further be classified as natural, synthetic natural, modified and artificial additives (Kamal and Fawzia, 2018; Faustino *et al.*, 2019; Martins *et al.*, 2019).

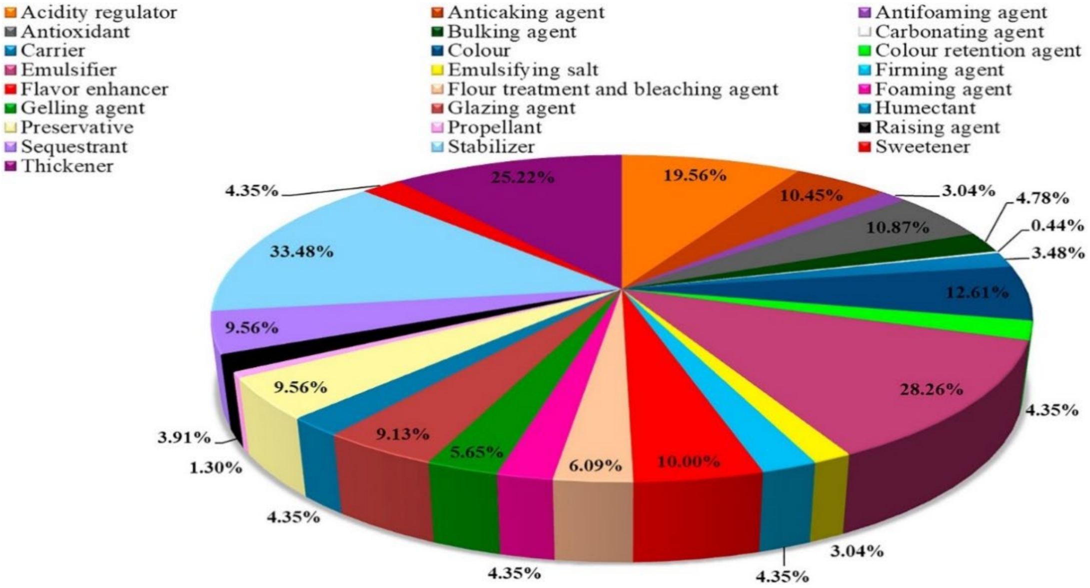

Figure 5.2: Percentual relationship of each class of food additives used in food industries (Martins *et al.*, 2019). Copyrights Elsevier.

The impact of food additives has been far-reaching; hence the World Health Organization (WHO) and other international forums promoting their inclusion in risk and safety activities, despite the scientific uncertainty of some contaminants (Pasca *et al.*, 2014). There are debates amongst the scientific community and various consumer interest groups regarding toxicologic studies and toxic levels. Residues such as bisphenol A, mineral oil aromatic hydrocarbons and synthetic amorphous silica are not well studied and there seems to be uncertainty regarding exposure assessments and potential health effects (Jansen *et al.*, 2020). At the consumer level, the influx of illegal food additives is perceived differently. Further, consumers' usage of food additives may be influenced by the market anchor price (Sha *et al.*, 2018; Zhong *et al.*, 2018; Faustino *et al.*, 2019). Essentially, their decision to use or not use additives is determined by intuition and experience due to their lack of expertise in food safety (Jansen *et al.*, 2020).

5.2.4. Preservatives

Food additives have several functions. Depending on the type, some may serve as chemical preservatives (Bruna *et al.*, 2018; Jayant and Halami, 2020). In recent years, the transformation in consumer needs and the food industry has led to non-conventional methods of ensuring high yields with minimal cost to producers. Consumers have gravitated towards high-energy food with a distinct flavour and reduced preparation time (Bruna *et al.*, 2018; Zhong *et al.*, 2018). The food industry stands to lose production if the food has a shorter shelf-life; therefore, technologies are used to curb the effect of food spoilage on the economy and company profits

(Bashir *et al.*, 2017). Preservatives are compounds that promote the reduction or prevention of microbial growth in various foods and products (Faustino *et al.*, 2019; Jayant and Halami, 2020). Moreover, preservatives can be synthetic or natural substances that are usually used in low concentrations to inhibit the growth of bacteria (Franco, Navarro and Martínez-Pinilla, 2019). Two classes can therefore be distinguished: Class I, which includes natural preservatives, and Class II, which contains chemical or synthetic preservatives. Examples of chemical preservatives include sorbate, benzoate and nitrates (Jayant and Halami, 2020). These synthetic preservatives pose a public health hazard in uncontrolled doses. Effects such as headaches, palpitations, allergies, vomiting and skin rashes have been documented in past studies (Kamal and Fawzia, 2018; Jayant and Halami, 2020). In other toxicologic studies, synthetic preservatives have been reported to have genotoxic and carcinogenic effects (Bruna, Thais and Lígia, 2018). A study in China between the years 2006 and 2015 revealed that 34.36% of all food safety incidents (N = 253,617) were a result of the illegal use of food additives.

5.3. Food packaging

Food packaging serves various functions in the food industry. The benefits extend from branding and advertising, barrier protection, protection from external elements and, to some extent, food preservation (Ng and Von Goetz, 2017; Han *et al.*, 2018; Mania *et al.*, 2018; Deshwal and Panjagari, 2020; Muncke *et al.*, 2020). Generally, food packaging encompasses a lot of processes whereby different food additives are used and blended with polymers to make the resultant material more durable (Nerín *et al.*, 2016; Sofi *et al.*, 2018). In food packaging, chemicals are intentionally applied in the manufacturing process and other materials are constantly in contact with food along the food production chain (Geueke, Groh and Muncke, 2018). It is well-documented that food packaging processes can introduce toxic contaminants in food, thus causing public health problems (Guerreiro *et al.*, 2018; Karmaus, Osborn and Krishan, 2018; Ernstoff *et al.*, 2019). Research shows that food-contact chemicals can have harmful effects on humans. Therefore, stringent measures need to be devised to address this challenge. Furthermore, these food-contact chemicals come in various ways, namely food packaging, food-storage containers, kitchen utensils and food-processing equipment (Bari and Yeasmin, 2018; Thompson and Darwish, 2019; Muncke *et al.*, 2020). The process of transferring and partitioning chemical compounds from food packaging into food through adsorption or diffusion is known as migration (Dainelli *et al.*, 2008; Ahmed *et al.*, 2018;

Guerreiro *et al.*, 2018). Essentially, migrants from packaging have the potential to cause adverse effects on human health.

Food-contact materials (FMCs) can release migrating substances. FMCs are reportedly the leading source of chemical contamination in food and significantly contribute to chronic chemical exposure (Geueke, Groh and Muncke, 2018). Migration of contaminants into foodstuffs depends on factors such as the composition of the material, package size, temperature, storage time, the nature of the food, and how it is exposed (Guerreiro *et al.*, 2018; Hahladakis *et al.*, 2018). As a result, food packaging is highly regulated internationally due to a vast range of literature on the carcinogenic effects of some of the chemical compounds used as ink and food-protective membranes (Mastromatteo *et al.*, 2010; Muncke *et al.*, 2020). In some instances, incorrect packaging methods, incorrect storage, and handling cause structural deficiencies in the packaging, thus leading to bloating of canned foods and sealants leaking into the food product. Moreover, corrosion through oxidation can alter the structural integrity of metallic containers, thus posing a health hazard. For this reason, metallic containers are coated with epoxy resin varnishes to curb corrosion (Nerín *et al.*, 2016). Typical migrants from contact materials are chemicals such as benzene, especially in the flavoured beverage industry. This chemical is used extensively in the manufacture of plastics and pesticides, and it is known to have carcinogenic properties. Another chemical compound used in the food industry is bisphenol A (BPA), which is used in the lining of some food and beverages to extend their shelf life (Bari and Yeasmin, 2018). It usually serves as a plasticizer in polymers like polyvinyl chloride (PVC) (Fred-Ahmadu *et al.*, 2020; Muncke *et al.*, 2020). Table 5.1 shows the types of packaging used in a variety of foodstuffs and how contamination is introduced.

Food products such as sugar, maize, flour, rice and most cereals are usually packaged in paper or board materials. For this reason, there are possibilities of chemical contamination by exposure to printing ink or, in extreme cases, absorption of moisture and chemical leaks when stored directly on the floor (Geueke *et al.*, 2018). Polymers are widely used in various applications in the food industry. Extensive research has progressed their usefulness in material design and general safety. Notably, polymers are used in food packaging and the most common are polyethylene, polyvinyl chloride, polystyrene, polycarbonate and polyethylene terephthalate (Nerín *et al.*, 2016). Phenolic endocrine-disrupting chemicals in food through food packaging have been largely reported in canned food, disposable plastic bottles, polyethylene terephthalate, etc. This happens by the migration of chemicals from food packaging over time after being exposed to conditions such as heat and normal tear and wear (Bajpai *et al.*, 2018; Deng *et al.*, 2019).

Researchers in one study assert that eco-friendly packaging might have passed tests in environmental sustainability and suitability; however, they warn that the human risk-factor tests are usually not documented rigorously for the same packaging material (Ernstoff *et al.*, 2019). Basically, in a life cycle test, a material can pass the first stage only to cause adverse effects in another phase. A human being is routinely exposed to harmful chemicals from a variety of sources such as food (Wang *et al.*, 2019). This calls for more toxicological studies to be conducted with mammalian subjects to measure the risk for individual chemicals. However, effective toxicological studies need to have well-defined and understood contaminants. This ensures that appropriate regulatory reviews are conducted to optimize testing for chemical migration levels (Karmaus *et al.*, 2018; Ramos *et al.*, 2018). Therefore, the identification of all chemicals inherent in the food and packaging material is critical. According to Karmaus *et al.* (2018), this process is completed through the evaluation of technical datasheets, supplier information, material-safety datasheets and compliance letters.

Table 5.1: Summary of selected food packaging and how contamination is introduced.

Type of Food	**Packaging Type**	**Contamination Pathways**	**References**
Rice	paperboard	Adhesives, coatings, inks	(Karmaus *et al.*, 2018)
Maize	paper	Migration, moisture, inks	(Deshwal, Panjagari and Alam, 2019)
Meat, Fish	polystyrene, corrugated fibreboard	Moisture in humid areas	(Deshwal *et al.*, 2019; Pilevar *et al.*, 2019)
Sugar	paper, paperboard	Absorption of moisture and chemicals.	(Deshwal *et al.*, 2019)
Raw and processed fruits/vegetables	polystyrene, metals, vegetable parchment paper, moulded pulp packaging	Moisture absorption and migration	(Deshwal *et al.*, 2019; Pilevar *et al.*, 2019; Deshwal and Panjagari, 2020)
Dairy	polystyrene plastics, metals, folding cartons	Migration and leaching chemicals	(Deshwal *et al.*, 2019; Pilevar *et al.*, 2019)
Bakery	polystyrene, greaseproof paper	Moisture absorption	(Pilevar *et al.*, 2019; Deshwal and Panjagari, 2020)
Beverages	metals, composite cans, foil wraps	Migration of bisphenol A Blackening, corrosion, bulging, tin dissolution, leaching coatings	(Adeyeye, 2019; Deshwal *et al.*, 2019; Deshwal and Panjagari, 2020)

5.3.1. Innovations in food packaging

The 20th century provided technological advancement regarding the use of smart packaging and active packaging (Janjarasskul and Suppakul, 2018). According to Yucel (2016), food packaging accounts for half of all packaging (Yucel, 2016). Contributions in the literature by various researchers show that the food industry has increased the use of flexible and plastic packaging such as low-cost polyester, alcohol-ethylene polymers and polypropylene (Yucel, 2016; Guerreiro *et al.*, 2018; Han *et al.*, 2018; Majid *et al.*, 2018). This rise in technological innovations provides opportunities for increased food safety, economic growth and reduced loss of products (Galstyan *et al.*, 2018). This increase in the use of technology is also influenced by trends in food demand. Mania *et al.* (2018) state that the "transregional and transnational long-distance" movement of food requires innovation to keep the food appealing to the consumers (Mania *et al.*, 2018). However, the use of new materials and technology can introduce foreign materials in unacceptable quantities. Active, green and intelligent packaging can introduce contaminants through chemical migration. Therefore, all food products must be labelled properly in consideration of the material used in packaging and the potentially toxic ingredients declared by legislation. Essentially, all additives in food packaging must be inspected and approved by an inspection authority or regulatory body.

Industrialization in the food industry has called for increased demand for the use of plastics in packaging. Plastics can be described as materials that are synthetic or natural polymers (Guerreiro *et al.*, 2018). Furthermore, they can be modified and manipulated using factors such as heat and pressure. Examples of plastics include bowls, foils, bags and bottles (Geueke *et al.*, 2018; Hahladakis *et al.*, 2018). Plastic materials are highly diverse and can be recycled. It is important to note that during recycling, polymers are partially degraded due to the breaking of intracellular bonds, leading to a change in their mechanical structure and appearance. During the recycling process, other non-intended chemicals may be introduced on the food-contact surface, leading to cumulative toxic chemical effects. The chemicals in the plastic can migrate in several ways; firstly, by direct contact of the food with the inner layer of the wrappings. Secondly, the chemical substance can indirectly pass one layer before being in contact with the food. Thirdly, it is possible that there may not be any physical contact. The space in food containers can be a mechanism for migration, especially with volatile substances (Freeman, 2018). For this reason, it is vital to conduct exposure assessments on all chemicals that can potentially be consumed as per the WHO recommendation (De Fátima Poças and Hogg, 2007).

Even though studies are constantly conducted to determine the toxicity of chemicals, they are usually executed using food simulants and focusing on specific compounds, not the final product. Fast screening of compounds from plastic packaging can be done; however, there are still challenges in determining the toxicity of the final food product.

5.4. Environmental chemical contamination

Environmental pollution is a widely documented burden in the ecosystem (Nerín *et al.*, 2016). More recently, the effects of such pollution have been reported to affect the food production chain. Amongst the major contaminants in the food production system, chemicals have been classified as a significant contributor to food contamination. The lack of management systems or weakened public health interventions, especially in high-density industrial areas of developing nations, has historically been linked with the contamination of food by chemicals (Nerín *et al.*, 2016; Deb, 2018). This supports the hypothesis that there is indeed a relationship between environmental contamination and public health, despite the association being poorly documented and reported. In many settings, it is difficult to quantify the extent of the contamination due to diverse contagions and a lack of advanced expertise.

There are multiple pathways to the contamination of food. The most common mediums contaminated by chemicals affecting the food industry are water, soil and direct contamination due to anthropogenic activities. Inadequate hygiene and poor sanitation are perceived to be among the leading causes of pollution and the manifestation of diseases globally (Deb, 2018). Water pollution in particular has a significant impact, as it is an essential part of any food. Moreover, the contamination of groundwater sources and changes in the chemical composition of water alter biotic and aquatic systems. There are two key water contamination types; firstly, a change in water's physical properties, as well as the amount of matter moved by the aquatic system; secondly, a change in the chemical composition of the aquatic body (Deb, 2018). Contamination can have a disastrous outcome in the food chain and, similarly, the food production chain can have a detrimental effect on water pollution. In agricultural environments, water runoff and chemical leachate can pollute water sources. Furthermore, manufacturing plants, including mining operations, can emit enough chemical pollutants to contaminate raw food products.

5.5. Persistent organic pollutants

Persistent Organic Pollutants (POPs) continue to be a threat to the environment due to continued emissions. The Stockholm Convention on POPs in 2001 restricted the usage of POPs; however, the resolution only came into effect in 2004 (Pius *et al.*, 2019). Long after the adoption by the conference committee, the continued exposure to POPs can be attributed to heavy industrial activities, which include the waste management sector and other industries that use additives and pesticides (Bruce-Vanderpuije *et al.*, 2019; Pius *et al.*, 2019). Persistent organic pollutants are carbon-based and can be in vapour form or as adsorbed by atmospheric particles (Gaur, Narasimhulu and PydiSetty, 2018; Volschenk *et al.*, 2019). The commonly known POPs are dioxins, dibenzofurans, organochlorine pesticides (OCPs), polycyclic aromatic hydrocarbons (PAHs) and PCBs (Gaur *et al.*, 2018; Guo *et al.*, 2019). Additionally, these compounds have been reported to have a long-lasting effect on the environment due to their non-degradable nature (Gaur *et al.*, 2018; Wang *et al.*, 2019). In Africa, the biggest contributor to POPs is pesticides. This is observed chiefly in countries where food production and trade contribute significantly to the gross domestic product (GDP). Furthermore, Ghana is reported to be one of the top pesticide users. In a review study in Ghana, dichlorodiphenyltrichloroethanes (DDTs) were found to be high risk in the studied food groups. However, the decline in some of the results is assumed to be a result of the Stockholm Convention Declaration (Bruce-Vanderpuije *et al.*, 2019). The researchers further note that people who are not exposed to POPs in their normal work environment are exposed through their dietary intake of animal products. Their exposure can be aggravated by the ingestion of fruits and vegetables contaminated by pesticides.

5.5.1. Polychlorinated biphenyls (PCBs)

Polychlorinated biphenyls (PCBs) are a group of manufactured synthetic chemicals falling under the umbrella of POPs. They were first produced in large quantities from the 1940s until the late 1970s; however, the first synthesis was in the 1880s (Loganathan and Masunaga, 2020). These chemicals have a clear colour and can be presented as solids or liquids. Historically, PCBs were used as lubricants, plasticizers and insulating oils for capacitors and transformers (Kang *et al.*, 2020). Furthermore, they are classified as persistent organic compounds due to their long-lasting effects on the environment. PCBs are known for their stable properties, thus being able to withstand temperature extremes and pressure. Generally, biphenyls can be formed through chemical the manipulation of various organic mixtures such as plastics and harvest-protection chemicals (Deb, 2018; Rusin *et al.*, 2019). Literature suggests that the common route of exposure to PBCs is through the ingestion of contaminated foodstuffs (Rusin *et al.*, 2019). Moreover, the highest levels of contamination have been noted in fish, meat, eggs and dairy products (Kang *et al.*, 2020). This is attributed to the high daily consumption of these foodstuffs. The ability of PCBs to infiltrate the food chain has been attributed to the fact that they are lipophilic, persistent and can accumulate in the environment for prolonged periods, notwithstanding that animals with a long lifespan have been reported to accumulate PCBs at high levels in their fatty tissues.

Earlier studies in Japan and Taiwan have reported food poisoning outbreaks as a result of PCBs in 1968 and 1979, respectively (Loganathan and Masunaga, 2020). In these studies, the contaminated foodstuff was rice, which is a staple food in these countries. Affected people exhibited symptoms such as pigmentation of the skin, numbness in the limbs, acne-like eruptions, and an abnormal discharge from the eyes (Loganathan and Masunaga, 2020). Other studies conducted in Lanzhou, China showed increased levels of PCBs in food, compared to non-industrialized areas. In this study, the highest concentrations were discovered in aquatic products (0.31 ± 0.30 ng/g). Furthermore, eggs and meat had the next-highest concentrations (0.08 ± 00.9 ng/g and 0.06 ± 0.05 ng/g). The results showed high levels of exposure, especially regarding the dietary intake of staple foodstuffs (Kang *et al.*, 2020). A review paper by African researchers supports the hypothesis that generally, urban development centres and industries account for the largest burden of PCB exposure in industrialized communities (Ssebugere *et al.*, 2019).

5.2.2. Pesticides

A pesticide is a common name for all plant-growth regulators, fungicides, herbicides, insecticides, rodenticides, molluscicides and nematicides (Kumar, Chand and Shah, 2018; Zikankuba *et al.*, 2019). Pesticides are widely used globally due to their benefits in controlling the manifestation of pests. They can be applied throughout the food production chain, i.e. farm, production, storage, transportation, distribution, processing and at the consumer level (Bhalla *et al.*, 2019; Volschenk *et al.*, 2019; Zikankuba *et al.*, 2019; Kosamu, Kaonga and Utembe, 2020; Tudi *et al.*, 2021). They are essentially chemicals used to mitigate pest outbreaks that cause plant diseases. They are known to affect “target as well as non-target species” (Deb, 2018; Xu *et al.*, 2021). The growth of the agricultural sector has also increased the usage of pesticides over the years. The first-generation pesticides were manufactured in the 1860s and later discontinued due to their toxic effect. In the 1870s, synthetic organic compounds were introduced (Kumar *et al.*, 2018). However, it was not until the 1940s that pesticides were manufactured and used extensively. In addition, the rise of industrial production in both developed and under-developed nations increased the usage of pesticides in their forests and crop fields. The general long-range transportation of pesticides makes them pollutants that transcend local, regional and national boundaries (Sharma *et al.*, 2019; Taiwo, 2019). Pesticide poisoning has a detrimental effect on human beings. As reported by Bhalla and colleagues, 250 000–370 000 people die every year due to the direct or indirect ingestion of pesticides (Bhalla *et al.*, 2019). Moreover, between the years 2010–2014, Japan was reported to use more pesticides than any country. This demonstrates a heavy reliance on pesticides in some countries due to a lack of cost-effective alternatives.

Figure 5.3 shows that there has been a steady increase in the study of the contamination caused by pesticides in food. Figure 5.3 shows the number of published studies from 2010 to March 2021 retrieved from the Web of Science core collection database (SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI). The Web of Science core collection database is known for its robust scientific authority and frequent use in bibliometric analysis by various researchers (Liao *et al.*, 2018). The closest matching search terms selected to identify publications by topic were ‘Pesticide food contamination’ and ‘Health effects’ or ‘contamination’. The search items produced 1 167 results from a wide variety of sources such as peer-reviewed articles, book chapters, review papers, etc.

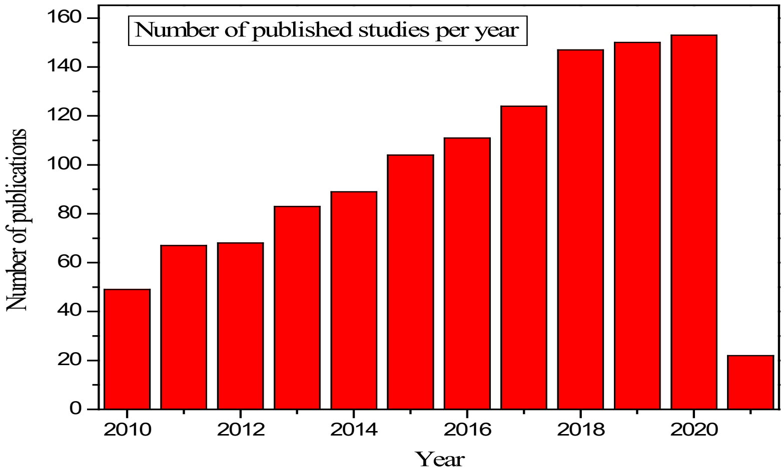

Figure 5.3: Pesticide contamination in food and the number of outputs per year. Data analysis was completed by the authors using the Web of Science databases on 04 March 2021.

Organophosphorus pesticides are the most-studied pesticides (Table 5.2). The contamination from these pesticides can be removed by using microorganisms in the process of bacterial degradation (Chiocchetti *et al.*, 2019; Massoud *et al.*, 2019). Past studies as reported by researchers have shown that lactic acid bacteria such as *Lactobacillus bulgaricus* and *Streptococcus thermophilus* can degrade pesticides (Chiocchetti *et al.*, 2019; Massoud *et al.*, 2019). Moreover, enzymes such as phosphodiesterase, methyl parathion hydrolases and organophosphorus acid anhydrolases can degrade organophosphorus pesticides. Other studies (Santarelli *et al.*, 2018) report *Saccharomyces cerevisiae* yeast during fermentation as a potent option in the removal or reduction of some pesticides in food. Therefore, to control the risk of pesticide exposure, risk assessment models need to be applied in food production industries and retailers to assess the level of pesticide residues (Santarelli *et al.*, 2018; Raymundo-Pereira *et al.*, 2021).

Table 5.2: Summary of the classification of pesticides and human health effects.

Pesticide name	Classification	Exposure/Pathway	Health effects	References
Dichlorodiphenyltrichloroethane (DDT)	Organochlorine	Ingestion, inhalation – Crop fields	Parkinson's disease, neurotoxic effects	(Bari and Yeasmin, 2018; Deb, 2018; Taiwo, 2019; Thakali and MacRae, 2021)
Hexachlorocyclohexane	Organochlorine	Ingestion of contaminated food	Birth defects in humans	(Khan *et al.*, 2019; Margenat *et al.*, 2019)
Benzene hexachloride	Organophosphates	Ingestion Locust control	Liver disease, skin lesions, loss of hair, thyroid damage, ulceration	(Santarelli *et al.*, 2018; Taiwo, 2019)
Malathion, chlorpyrifos, diazinon, temephos	Organophosphates	Ingestion	Neurologic toxic effects, impaired vision, headache, dizziness	(Rather *et al.*, 2017; Han *et al.*, 2018; Ramos *et al.*, 2018; Deng *et al.*, 2019)

According to Kumar *et al.* (2018), approximately 80% of all pesticides globally are produced in developed nations annually (Kumar *et al.*, 2018). Moreover, farming activities account for approximately 70–80% of pesticide use. Their application on vegetables alone in developed countries is estimated to be around 25% (Zikankuba *et al.*, 2019). It has been cited that only 0.1% of pesticides reach the intended pest, and the remaining 99.9% proliferate in the surrounding environments i.e., food, water, air, etc. (Deb, 2018). Essentially, pesticides are transported in environments through various ways such as water runoff, spreading through the vapour, leaching into substances, and shifting from different places through osmosis under the influence of air circulation (Kumar *et al.*, 2018; Zikankuba *et al.*, 2019).

There are about 1 400 known pesticides (Bari and Yeasmin, 2018). Some pesticides such as DDT have long been banned in some countries. However, bioaccumulation is still detected in some streams due to the lasting effects of the chemical compounds (Mazzoni *et al.*, 2018). Therefore, rigorous monitoring standards and regulations need to be adhered to across national borders (Taiwo, 2019). In risk assessment studies, it has been found that the cocktail effect of chemicals is even more dangerous due to multiple exposure pathways (Margenat *et al.*, 2019). Essentially, the additive effect of one compound is heightened when it is combined with another. DDT can last in the soil for years until it enters the food chain through adsorption and eventually contaminates the food. Other chemical compounds such as organochlorine pesticides (OCPs) have been widely studied in recent years due to their agricultural use (Taiwo, 2019). These OCPs are known for their chemical qualities (Figure 5.4). Over the years, they have been reported to be almost everywhere, persistent, hydrophobic, and resistant to degradation. Organochlorine pesticides are chemically stable and semi-volatile, which implies that they last longer in environments and can be transported easily in the atmosphere through the wind, and they are known to be lipophilic. This trait allows them to attach easily to animal and human fatty tissues. OCPs are majorly found in fatty foods due to their fat solubility, e.g. fish, meat and dairy products. African countries such as Togo, Nigeria and Ghana still report figures higher than the maximum permissible limits due to their extensive use (Taiwo, 2019).

5.1.1. Pesticides and food safety

Daily consumption of food comes with potential daily exposure to pesticides. Most countries have pre-determined maximum permissible limits as recommended by FAO/WHO/*Codex Alimentarius.* In Europe, the European Food Safety Authority (EFSA) conducts independent research on risk assessments and further advises authorities on permissible levels. Essentially, the EFSA functions as a gatekeeper to the European Commission regarding the approval of new substances and setting new maximum residue levels after completing their rigorous peer review and due diligence on potentially harmful substances (Food and Authority, 2011; European Food Safety Authority, 2019). In cases where pesticide residues exceed the maximum residue level, the exposure must be compared with the acceptable daily intake (ADI) and/or the Acute Reference Dose (ARfD) to assess the risk for the consumer (Zikankuba *et al.*, 2019). Researchers define ADI as "the number of pesticides in mg/kg to which humans can be exposed daily through ingestion during a lifetime without appreciating risks to the health on the bases of all known facts at the time of evaluation" (Nasreddine and Parent-Massin, 2002; Zikankuba *et al.*, 2019). On the other hand, the ARfD is established for the general population based on children and infants, including women who are considered to be of childbearing age. Essentially, it is the exposure level at which harmful effects are likely to occur in the most sensitive individuals in a population during a single-day exposure, within 24 hours. Member countries affiliated with the WHO have established threshold limits for food contaminants to comply with recommendations as defined in the *Codex Alimentarius*. Table 4.3 shows the maximum allowable levels of pesticide residue that may be present in the food according to the *Codex Alimentarius* standards.

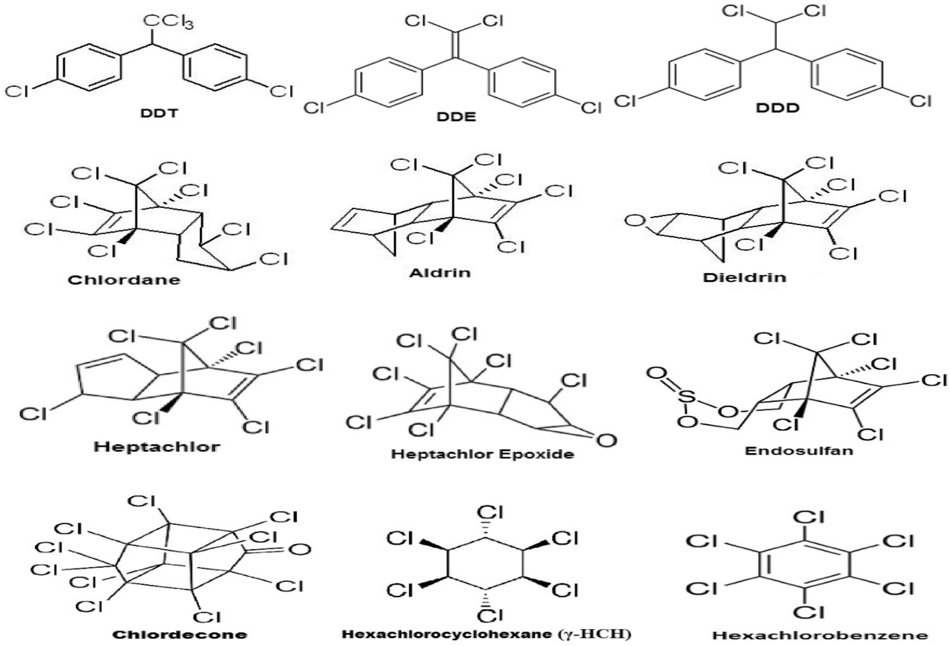

Figure 5.4: Structure of some of the organochlorine compounds (Taiwo, 2019). © Elsevier**.**

Table 5.3: Maximum levels for selected pesticides that may be present in foodstuffs as per the *Codex Alimentarius* International Food Standards (FAO, 2021)

Pesticide	**Foodstuff**	**Maximum Residue Levels (MRL) (mg/kg)**
Abamectin	Citrus fruits	0.02
	Soya beans (dry)	0.002
Acephate	Cabbages, head	2
	Meat (From mammals other than marine mammals	0.05
DDT	Carrot	0.2
	Cereal grains	0.1
	Poultry meat	0.3
Azoxystrobin	Strawberry	10
	Sunflower seed	0.5
	Banana	2
	Soya bean (dry)	0.5
	Sorghum	10
	Sugar cane	0.05
	Poultry meat	0.01
	Rice	5
Tebuconazole	Apples	1
	Apricot	2
	Barley	2
	Broccoli	0.2
	Carrot	0.4
	Coffee beans	0.1
	Prunes, dried	3
	Tomato	0.7
	Wheat	0.15

5.6. The use and effects of antibiotics in the food industry

The history of the use of antibiotics in agriculture can be traced as far as 1935 by German pharmaceutical manufacturers (Kirchhelle, 2018). There have been significant strides in technology relating to usage and rapid manufacturing processes in food safety industries. Antibiotics can be viewed as chemical compounds used to inhibit the growth of bacteria (Baynes *et al.*, 2016; Zhao *et al.*, 2018). These antibiotics can be produced naturally or synthetically in laboratory conditions (Wang *et al.*, 2017; Roca-Saavedra *et al.*, 2018; Bacanlı and Başaran, 2019). They have been used extensively in medical applications over the years due to the high demand for medical drugs for human and animal health (Bari and Yeasmin, 2018; Njoga *et al.*, 2018; Ahmad *et al.*, 2019). This demand has seen an increased risk of exposure of humans to various antibiotics, both as a by-product or by direct ingestion. In particular, the risk can be the result of a prolonged intake of contaminated food products. Crops and meat products serve as examples of typical foods that may be exposed to antibiotics. In animal farming, antibiotics are hazardous to humans when no quality control measures are observed, thus resulting in humans consuming them in large and unsafe quantities (Hu and Cheng, 2016; Bacanlı and Başaran, 2019). According to Bacanli and Barasan (2019), 80% of animals used in food production are currently treated with veterinary drugs or will be throughout their lifetime (Bacanlı and Başaran, 2019). Therefore, it is vital for the food industry to constantly analyse the methods and standards used in the administration of antibiotics to avoid food-borne drug residues. These food-borne drug residues can cause both chronic and acute health effects. Table 5.4 summarizes some of the antibiotics in food, including their human health effects.

The main use of antibiotics in food animals as suggested by various sources of literature include the prevention of diseases and promoting growth (Hu and Cheng, 2016; Scott *et al.*, 2018; Bacanlı and Başaran, 2019; Sivagami *et al.*, 2020). Antibiotics can be administered in various ways such as orally or parenterally. Thus, incorrect handling and application can be a public health disaster. The residues in foodstuffs can cause adverse effects on human health. Additionally, contamination occurs through feed, drinking water, food processing equipment, and processes (Sivagami *et al.*, 2020). The excreted antibiotic dose (30–80%) provided to food animals can enter the environment through manure or fertilizer, which can ultimately be used as a plant nutrient or animal feed, thus completing the vicious cycle in the food chain (Moudgil *et al.*, 2018; Sivagami *et al.*, 2020). Various ethical and environmental issues regarding the use of antibiotics have been debated in recent years. Chief among the ethical issues is animal health regarding the procedures for administering antibiotics. Inappropriate therapy can further cause antibiotic resistance in both animals and farmworkers (Van *et al.*, 2020). Figures 5.5 and 5.6 illustrate the exposure routes of antibiotics, the transfer of resistance genes to humans, and the fate of veterinary antibiotics.

Table 5.4: Summary of the classification of antibiotics and human health effects.

Pesticide Name	Class	Documented Health Effects	References
Oxytetracycline	Tetracyclines	Poor teeth development in young children and stained dental enamel, loss of appetite, diarrhoea	(Gonzalez Ronquillo and Angeles Hernandez, 2017; Wang *et al.*, 2017; Manage, 2018)
Pleuromutilin	Timulin	Suspected metabolic instability, hepatotoxicity, concerns around cardiac safety, lack of sufficient oral bioavailability, gastrointestinal side effects	(Novak, 2011; Kang *et al.*, 2018; Mehdi *et al.*, 2018)
Ampicillin	Aminopenicillins	Angioedema. It can cause stomach cramps, diarrhoea, dizziness, and rashes nausea. Overdose can cause confusion, blackouts, and renal failure	(Manage, 2018; Mehdi *et al.*, 2018; Bagheri and Ghaedi, 2020)
Erythromycin	Macrolides	Abdominal pain, cramping, nausea, vomiting, and diarrhoea	(Tenenbein and Tenenbein, 2005; Manage, 2018)
Sulphonamides	Sulphonamides	Pruritic rashes, gastrointestinal distress, hematologic abnormalities and fever.	(Manage, 2018; Zhao *et al.*, 2018)
Difloxacin	Quinolones	May cause central nervous system toxicity, especially in animals with renal failure. May cause some nausea, vomiting, and diarrhoea at high doses	(Kang *et al.*, 2018; Zhao *et al.*, 2018)
Enrofloxacin	Quinolones	Central nervous system stimulation may lead to restlessness, tremors, confusion, and hallucinations	(Kang *et al.*, 2018; Zhao *et al.*, 2018)
Flumequine	Quinolones	Adverse reactions were observed, including vomiting	(Kang *et al.*, 2018)
Nalidixic acid	Quinolones	Convulsions, increased intracranial pressure, and toxic psychosis	(Kang *et al.*, 2018)
Oxolinic acid	Quinolones	Nervous excitation, stereotyped behaviour, and insomnia	(Kang *et al.*, 2018; Zhao *et al.*, 2018)
Trimethoprim	Potentiator	Pruritic rashes, gastrointestinal distress, hematologic abnormalities, and fever	(Mehdi *et al.*, 2018; Zhao *et al.*, 2018)

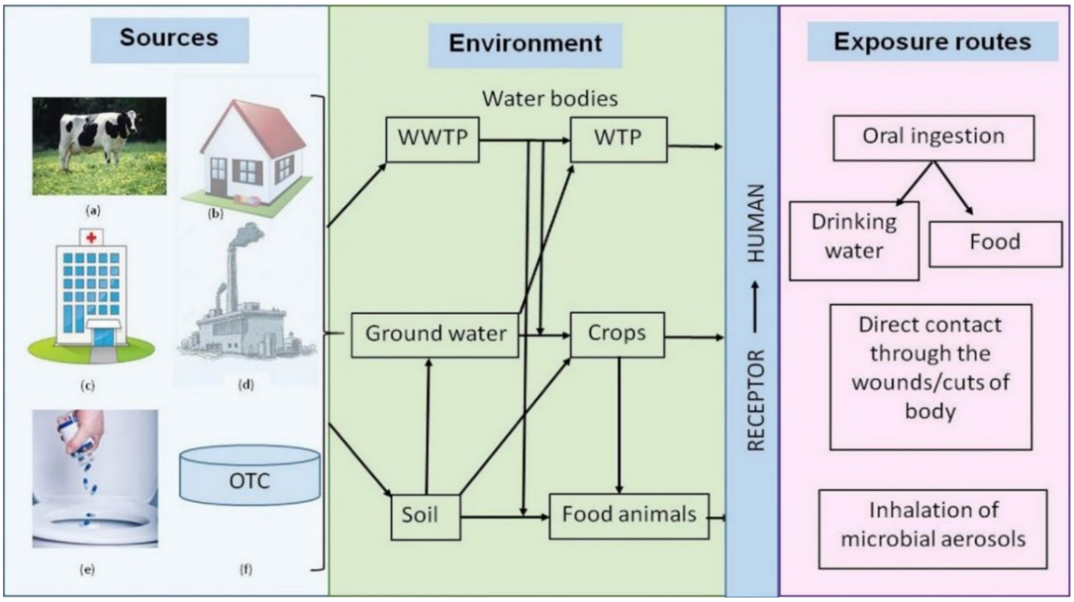

Figure 5.5: Sources of antibiotic usage, its spread, and transfer of resistance genes to humans.

The excessive usage of antibiotics as growth stimulants in livestock and other food animals can contaminate water sources when animal excreta is washed off with water into the environment. (a) The contamination of sewage treatment plants can be a result of excessive human usage of antibiotics. (b) Hospitals and pharmaceutical industries contribute significantly to wastewater treatment plants' pollution by antibiotics when they are illegally let into sewage systems. (c) (d) Improper disposal of antibiotic pills and unprescribed over-the-counter antibiotics can contaminate wastewater treatment plants. (Sivagami *et al.*, 2020). Copyright Elsevier.

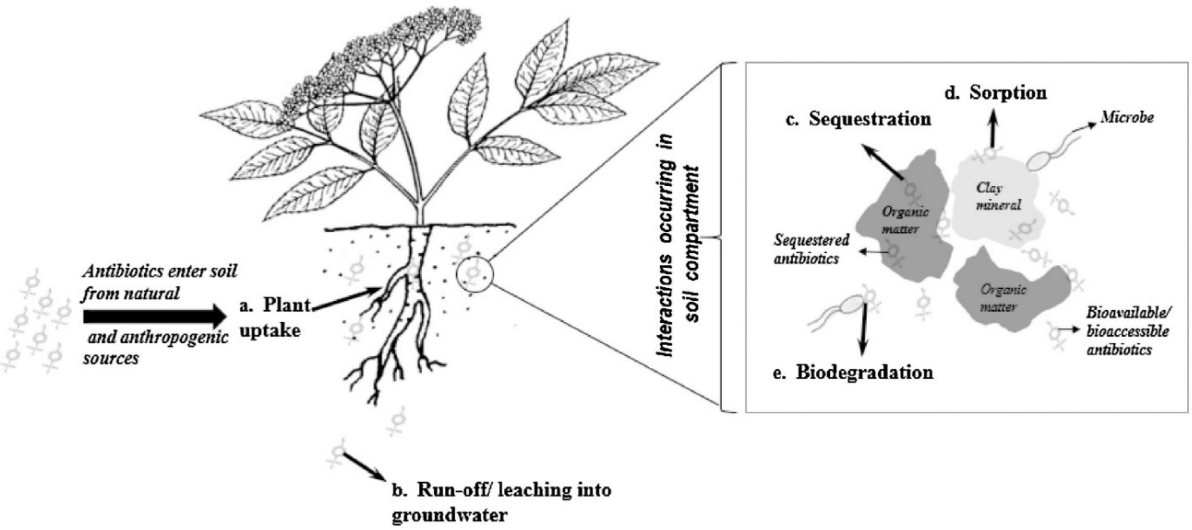

Figure 5.6: Fate of veterinary antibiotics (Kuppusamy *et al.*, 2018). Copyrights Elsevier.

5.7. Heavy metals

Various metals are essential for living organisms; however, at an excessive concentration, they can be detrimental to human health (Antoniadis *et al.*, 2019; Setia *et al.*, 2021). Literature shows that certain elements are studied more than others according to geographical location (Antoniadis *et al.*, 2019). According to Antoniadis *et al.* (2019), metallic elements such as nickel, copper, iron, aluminium, manganese, chromium, cadmium, lead, argon, zinc and arsenic have received more attention in literature with regard to human health impacts (Antoniadis *et al.*, 2019). The researchers assert that this could be attributed to their significance in the human food chain, especially concerning the allowable maximum daily dietary intake. The researchers also mention an interesting narrative about crop production areas and their locality. Essentially, the more an area is used for agricultural produce, the more industrial parks grow around it. In turn, industrial activities will contaminate the food through the water table and the air, thus affecting human health. This is supported by Al-Othman *et al.* (2016) and Rai *et al.* (2019), who reveals the long-term degradation of the quality of the environment and adverse human health effects as a result of industrialization. This provides conclusive evidence that plants grown in polluted environments can be a vehicle for contaminants to be introduced into the food chain. Therefore, organizations such as the European Chemical Agency came up with strategies to protect human health by heavily regulating the use of chemicals. This ensures control through the identification of hazardous substances and monitoring (De Tandt *et al.*, 2021).

Heavy metals are metallic chemical elements that may be toxic and poisonous when untreated. They are known to bioaccumulate and persist in the environment. Moreover, they can enter the human body through direct contact or ingestion of contaminated foodstuffs (Chiesa *et al.*, 2019). Fish contaminated with methylmercury from industrial effluents have been reported in the past where neurological symptoms were seen in patients who consumed the fish (Deb, 2018). Sustenance is essential for human life; therefore, exposure to factors adverse to human health through foodstuffs is of high importance. The scarcity of food in developing countries increases the risk of exposure to harmful untreated metals. In communities relying on aquatic food for sustenance, the risks of digestive ailments are high, especially when exposed to metals such as copper (Cu), which is known for causing digestive discomfort in susceptible individuals. Heavy metals are majorly introduced in the human body through two common pathways; firstly, the inhalation of contaminated air; secondly, the ingestion of contaminated water and food plants grown in the regions where the soil is contaminated (Al-Othman *et al.*, 2016; Marini *et al.*, 2021). In addition, in studies assessing the presence of toxic metals in wheat crops grown on selected soils irrigated by different water, researchers discourage the propagation of wheat plants near highly industrialized areas due to the heavy metals' tendency to accumulate in the aerial parts of the plants, thus explaining phytotoxic properties of the metallic compounds (Al-Othman *et al.,* 2016; Marini *et al.,* 2021).

Figure 5.7 shows that there has been a consistent gradual increase in the study of heavy metals in food in terms of the number of published studies since the year 2010. The graph shows the number of published studies from 2010 to 04 March 2021, as recorded by the Web of Science core collection database (SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI) using the search string 'Heavy metal contamination in food'.

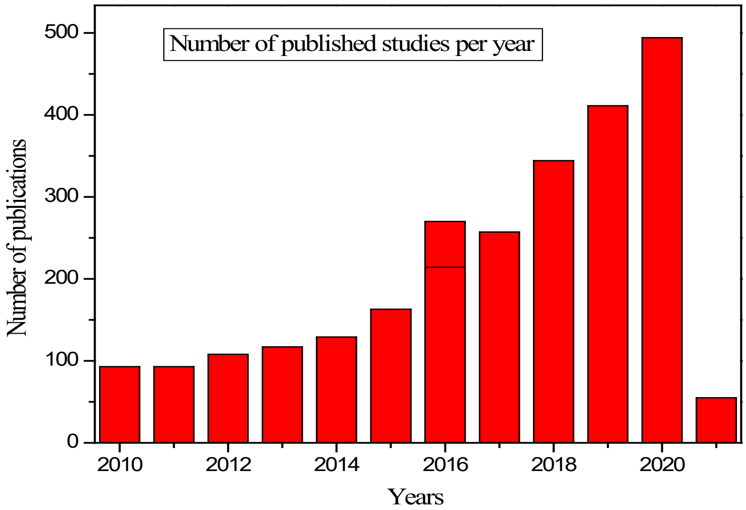

Figure 5.7: Heavy metal contamination in food and the number of outputs per year.

Data analysis was completed using the Web of Science database by the authors on 04 March 2021.

5.7.1 Pathway of heavy metals

Heavy metals are transferred along the plant pathway in various ways. The most common way is through soil spores to plants in ionic forms (Rai *et al.*, 2019; Hejna *et al.*, 2021). The capillarity of plants enhances the translocation of heavy metals to the rest of the plant. Therefore, the concentration of heavy metals in plants may vary according to the different parts of the crop plants, i.e., roots, leaves and fruits. The roots of the plants play a vital role in the rate of metal absorption and translocation to the rest of the plant. Different crop species have membranes that may be more adapted to rapid absorption than others (Al-Othman *et al.*, 2016; Mihaileanu *et al.*, 2019; Afonne and Ifediba, 2020; Khezerlou *et al.*, 2020). A study was conducted in Nigeria whereby a Transfer Factor (TF) for four heavy metals was analysed in five different vegetables that grew near the discharged wastewater sites. The most prominent result in the study was the high TF of Cadmium (Cd) in the Irish potato (TF of 2.88), attributed to the concentration of metals in the soil. The overall TF of accumulated cadmium in the overall samples was 6.52×10^{-5}–2.88, while Lead (Pb) had the lowest accumulation, with a TF of 0.23–0.34. Further analysis showed that chromium and cadmium were above the maximum permissible limits for vegetable consumption (Edogbo *et al.*, 2020).

One important factor to consider is the significance of crops such as wheat and maize in developing nations such as South Africa. These crops form the country's staple foods or national diet. They are distributed and sold to communities that may already be immuno-compromised or already under community or household level of food insecurity. The populations likely to be affected include schools under national school feeding and nutrition programmes, hospitals, prisons, and indigents receiving food parcels. This is because the above-mentioned population groups do not have a range of options regarding what they can consume. In Southern Africa, food products such as maize and peanuts are considered primary staples (Misihairabgwi *et al.*, 2019) and contribute significantly to the economy in the southern region. The researchers state that quality crops are exported, while poor crops are left for local consumption. This can be attributed to the high demand and standards of developed nations. The typical climatic conditions (warm and humid) in the southern region are conducive to the manifestation of toxin-producing fungi and possibly the disintegration of certain polymers used in food packaging.

Maize in South Africa is a staple that is usually consumed fresh or processed, cooked, or fermented. Another factor is the contamination of vegetables by metals in peri-urban or rural agricultural holdings. Therefore, along the production chain, maize could be contaminated by metals in the soil. By implication, subsistence farmers, especially in the rural parts of the country, may be exposed to the adverse effects of contaminated food. Table 5.5 shows the maximum allowable limits for heavy metals allowed in foodstuffs, according to the *Codex Alimentarius* International Standards for Food. The higher chemical concentration exposure by agrochemicals and trace elements can be attributed to the location of the heavy industries, which are usually located outside the city centres as per town planning schemes (Margenat *et al.*, 2019).

Table 5.5: Maximum levels of selected metals in foodstuffs as determined by in the *Codex Alimentarius* International Food Standards (*Alimentarius*, 2009).

Metal	**Foodstuff**	**ML (mg/kg)**
Arsenic, Total (As-tot)	Edible fats and oils	0.1
	Olive oil, refined	0.1
	Margarine	0.1
	Vegetable oil, crude	0.1
Cadmium (Cd)	Brassica vegetables	0.05
	Bulb vegetables	0.05
	Fruiting vegetables (Excluding tomatoes & edible fungi)	0.05
	Leafy vegetables	0.2
	Legume vegetables	0.1
Tin (Sn)	Canned beverages	150
	Cooked cured chopped meat (Applies to products in containers other than tinplate containers)	50
	Cooked cured ham (Applies to products in containers other than tinplate containers)	50
	Corned beef (Applies to products in containers other than tinplate containers)	50
Lead (Pb)	Fruits, except berries and other small fruits (After removal of the stem, cap, stone, crown, and/or seeds but calculated on whole fruit	0.1
	Brassica vegetables	0.1
	Bulb vegetables	0.1
	Fruiting vegetables (Excluding fungi and mushrooms)	0.05
	Leafy vegetables	0.3
	Legume vegetables	0.1
	Canned fruits	0.1
	Canned vegetables (Excluding canned brassica vegetables)	0.1
	Fruit juices, nectars, and ready-to-drink fruit drinks/juices (Excluding juices and nectars from berries and small fruits and passion fruit juices	0.03
	Poultry, Edible offal of	0.5
	Fish (whole commodity or portions, without the viscera).	0.3
	Milk	0.02
	Secondary milk products (Products made from milk)	0.02
	Infant formula, a formula for special medical purposes intended for infants and follow-up formula	0.01

5.8. Food Safety Laws

There has been an increase in the international trade of food globally. Developed nations have come up with innovative and stringent measures to protect against food contamination through food safety management systems that aim to improve traceability and transparency from partner countries (Yapp and Fairman, 2006; Chen *et al.*, 2020; Crépet *et al.*, 2021). Moreover, it is reported that suppliers along the food production chain are increasingly showing their importance in food safety and the application of international and regional laws. This is due to incidents of failing food safety management systems threatening food safety in recent times across the world. The WHO and the Food and Agriculture Organization (FAO) have joined forces in terms of defining and setting international standards for food safety regarding safe exposure levels and educational programmes. The regulatory measures and laws by these organizations are meant to promote quality and safe food supply to participating member states across the world (Crépet *et al.*, 2021). Furthermore, the interventions agreed upon by these organizations gave rise to committees on food additives established in 1965 and the expert committee on pesticide residues (Bhalla *et al.*, 2019). The FAO/WHO collaboration also had the *Codex Alimentarius* initiative established in 1963, which aims to supervise and facilitate the refinement of definitions and requirements for food to make transboundary standards consistent. The *Codex Alimentarius* has committees mandated to deliver specific standards in selected food commodities. Notably, the codex committee on contaminants in food (CCCF) (Thompson and Darwish, 2019), the codex committee on pesticides residues (CCPR) (Ambrus and Yang, 2016), and the codex committee on residues of veterinary drugs in food (CCRVDF) (Delatour *et al.*, 2018). These committees are set up to establish standards and develop a code of practice for contaminants in food. This includes methods of sampling, analysis and maximum exposure limits (European Food Safety Authority, 2019).

Food safety incident rates gave rise to the promulgation of the ISO 22000 international standard for establishing food safety management standards. This standard has seen several revisions from ISO 22000:2005 to the current ISO 22000:2018. It has come with opportunities and challenges in its interpretation and application. Essentially, this standard aims to assist organizations with the optimal allocation of resources, improve communication internally and externally, document organizational performance, build consumer trust and monitor management performance (Bhalla *et al.*, 2019; Chen *et al.*, 2020). Over the years, most organizations have used a common hazard analysis critical control point system (HACCP); however, it has come under scrutiny in recent years for its application in small- and medium-sized enterprises (Chen *et al.*, 2020). The main criticism was regarding organizations’ over-reliance on applying critical control points in operation without the adequate training the ISO 220 000 standard recommends. Ultimately, a tiered approach of different standards is recommended to effectively deal with dynamic food safety concerns.

5.9. Regulatory strategies

Organizations are encouraged to adopt self-regulatory approaches where they can use external approval from inspection authorities to monitor the food safety compliance levels within the organization. In the United Kingdom, the government compels companies to design a set of policies and laws and then an external company audits the company against the set standards (Yapp and Fairman, 2006). This process is done through hazard analysis by identifying risk factors inherent to the business and ultimately the consumers. The other regulatory strategy is enforced by Environmental Health Practitioners (EHPs) who are usually appointed by local authorities. They play an advisory and educational role within the food industry. Other functions include issuing statutory notices, premises closure and prosecution (Yapp and Fairman, 2006). In a study in the UK, money was found to be an important element to prompt small–medium enterprises to comply with food safety standards. Finances need to be considered when designing food safety protocols and their impact. Companies can be reluctant to spend money on food safety measures due to a lack of commitment to food safety. As a consequence, consumers will be negatively affected.

The regulation of the food industry and consumer behaviour in food safety matters is a challenge in South Africa. In the food retail sector, there have been numerous reports on bacterial infections and pesticide residues on foodstuffs distributed for sale (Boatemaa *et al.*, 2019). Factors leading to food contamination include unhygienic food preparation and, in some cases, sheer negligence by both the retail sector and consumers. The food retail sector is the leading cause of food-safety incidents, due to the vast supply chain and the sector being the last stage before the food reaches the consumers (Boatemaa *et al.*, 2019). South Africa is an emerging economy and the food industry has been reported to have contributed 9% to the overall gross domestic product in the year 2016 (Boatemaa *et al.*, 2019). This can be attributed to the dominance of supermarkets and farms that supply them.

Southern Africa and the rest of Africa largely depend on agriculture for subsistence (Pius *et al.*, 2019). In South Africa, the food industry is regulated by three departments, namely the Department of Trade and Industry (DTI), The National Department of Health (NDoH), and the Department of Agriculture, Forestry and Fisheries (DAFF). These departments are further entrusted to oversee certain sets of legislation according to expertise and designation. The *Consumer Protection Act (Act 68 of 2008)* is enforced by DTI, and it supersedes all food-related legislation in South Africa. The second in the hierarchy of powers is the NDoH, which is mandated to enforce the *National Health Act, related amendments (Act 61 of 2003),* and the *Foodstuffs, Cosmetics and Disinfectants Act 54 of 1972).* The Department of Agriculture, Fisheries, and Forestry is entrusted with the enforcement of the *Agricultural Product Standards Act 119 of 1990.* All these pieces of legislation combined form the core of the South African food control system.

5.10 Conclusions

The study of chemical toxicity in the food industry is fundamental and needs to be supported by rigorous toxicological studies. This will improve the quality of food products offered by the food industry and will ultimately benefit consumers. Heavy metals, antibiotics and POP contamination can cause adverse human health effects and thus needs regulation through adequate legislative interventions and proper monitoring standards supported by sound scientific data. The already existing interventions such as the bioremediation of pollutants are effective. However, more research needs to be conducted on the sustainability and financial impact of these solutions as a control strategy in the food industry. This review revealed a plethora of studies that could be undertaken to further narrow the toxicological effects of chemicals on food sources.

Further research might explore how toxic chemicals in food are transferred from farms to consumers in developing countries. This kind of toxicological study might compare the toxicological effects by region and even the proximity of exposure to food sources and the environmental drivers of food contamination. Threshold limits need to be developed for various chemicals at low concentrations. An in-depth study could further explore the food safety management systems in place at the national level of food control including the relationships with stakeholders and consumers. This paper highlighted that most studies on heavy metal exposure were conducted in Asian countries such as China and Japan, notwithstanding the contribution of the European Union through the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH). Significant work has been carried out to foster compliance in Europe through the regulation of chemicals in various industries including the agricultural sector. However, more methodological work needs to examine and test the same studies in a new context, such as Africa; thus, comparing the types of exposure from a broad spectrum such as cultural diversity, food staples, food safety systems, and climatic variations in agricultural land.

Illnesses caused by chemical exposure in food need to be studied across all agriculture-intensive countries. Methods to capture the economic impact of illnesses caused by chemical contamination in food robustly need to be designed and aligned with global goals on sustainability and best practices. It would also serve a great purpose to involve the food industry in expressing their challenges regarding systems of producing food with minimal chemical contamination.

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5.11. References

Adeyeye, S. A. O. (2019) 'Food packaging and nanotechnology: safeguarding consumer health and safety', *Nutrition and Food Science*, 49(6), pp. 1164–1179. doi: 10.1108/NFS-01-2019-0020.

Afonne, O. J. and Ifediba, E. C. (2020) 'Heavy metals risks in plant foods – need to step up precautionary measures', *Current Opinion in Toxicology*, 22, pp. 1–6. doi: 10.1016/j.cotox.2019.12.006.

Ahmad, S. *et al.* (2019) 'Risk Management of Chemical Hazards Arising During Food Manufacturing', in *Health and Safety Aspects of Food Processing Technologies*, pp. 403–418. doi: 10.1007/978-3-030-24903-8_13.

Ahmed, I. *et al.* (2018) 'An overview of smart packaging technologies for monitoring safety and quality of meat and meat products', *Packaging Technology and Science*, 31(7), pp. 449–471. doi: 10.1002/pts.2380.

Aiyar, A. and Pingali, P. (2020) 'Pandemics and food systems - towards a proactive food safety approach to disease prevention & management', *Food Security*, 12(4), pp. 749–756. doi: 10.1007/s12571-020-01074-3.

Alimentarius, C. (2009) *CODEX STAN 193-1995 Page 1 of 44*, *Natural Toxins*.

Al-Othman, Z. A. *et al.* (2016) 'Assessment of toxic metals in wheat crops grown on selected soils, irrigated by different water sources', *Arabian Journal of Chemistry*, 9, pp. S1555–S1562. doi: 10.1016/j.arabjc.2012.04.006.

Ambrus, Á. and Yang, Y. Z. (2016) 'Global Harmonization of Maximum Residue Limits for Pesticides', *Journal of Agricultural and Food Chemistry*, 64(1), pp. 30–35. doi: 10.1021/jf505347z.

Antoniadis, V. *et al.* (2019) 'Soil and maize contamination by trace elements and associated health risk assessment in the industrial area of Volos, Greece', *Environment International*, 124 (January), pp. 79–88. doi: 10.1016/j.envint.2018.12.053.

Bacanlı, M. and Başaran, N. (2019) 'Importance of antibiotic residues in animal food', *Food and Chemical Toxicology*, 125, pp. 462–466. doi: 10.1016/j.fct.2019.01.033.

Bagheri, A. R. and Ghaedi, M. (2020) 'Magnetic metal organic framework for pre-concentration of ampicillin from cow milk samples', *Journal of Pharmaceutical Analysis*. doi: 10.1016/j.jpha.2020.02.006.

Bajpai, V. K. *et al.* (2018) 'Prospects of using nanotechnology for food preservation, safety, and security', *Journal of Food and Drug Analysis*, 26(4), pp. 1201–1214. doi: 10.1016/j.jfda.2018.06.011.

Bari, M. L. and Yeasmin, S. (2018) 'Foodborne Diseases and Responsible Agents', in Grumezescu, A. M. and Alina Maria, H. (eds) *Food Safety and Preservation*. Elsevier Inc., pp. 195–229. doi: 10.1016/b978-0-12-814956-0.00008-1.

Bashir, K. M. I. *et al.* (2017) 'Natural Food Additives and Preservatives for Fish-Paste Products: A Review of the Past, Present, and Future States of Research', *Journal of*

Food Quality, 2017. doi: 10.1155/2017/9675469.

Baynes, R. E. *et al.* (2016) ‘Health concerns and management of select veterinary drug residues’, *Food and Chemical Toxicology*, 88, pp. 112–122. doi: 10.1016/j.fct.2015.12.020.

Bernardi, A. O., Garcia, M. V. and Copetti, M. V. (2019) ‘Food industry spoilage fungi control through facility sanitization’, *Current Opinion in Food Science*, 29, pp. 28–34. doi: 10.1016/j.cofs.2019.07.006.

Bhalla, T. C. *et al.* (2019) ‘International laws and food-borne illness’, in Singh, R. L. and Mondal, S. (eds) *Food Safety and Human Health*. Elsevier Inc., pp. 319–371. doi: 10.1016/B978-0-12-816333-7.00012-6.

Boatemaa, S. *et al.* (2019) ‘Awakening from the listeriosis crisis: Food safety challenges, practices and governance in the food retail sector in South Africa’, *Food Control*, 104 (January), pp. 333–342. doi: 10.1016/j.foodcont.2019.05.009.

Bruce-Vanderpuije, P. *et al.* (2019) ‘The state of POPs in Ghana- A review on persistent organic pollutants: Environmental and human exposure’, *Environmental Pollution*, 245, pp. 331–342. doi: 10.1016/j.envpol.2018.10.107.

Bruna, G. O. L., Thais, A. C. C. and Lígia, A. C. C. (2018) ‘Food additives and their health effects: A review on preservative sodium benzoate’, *African Journal of Biotechnology*, 17(10), pp. 306–310. doi: 10.5897/ajb2017.16321.

Chen, H. *et al.* (2020) ‘Food safety management systems based on ISO 22000:2018 methodology of hazard analysis compared to ISO 22000:2005’, *Accreditation and Quality Assurance*, 25(1), pp. 23–37. doi: 10.1007/s00769-019-01409-4.

Chiesa, L. M. *et al.* (2019) ‘Food risk characterization from exposure to persistent organic pollutants and metals contaminating eels from an Italian lake’, *Food Additives and Contaminants - Part A Chemistry, Analysis, Control, Exposure and Risk Assessment*, 36(5), pp. 779–788. doi: 10.1080/19440049.2019.1591642.

Chiocchetti, G. M. *et al.* (2019) ‘Use of lactic acid bacteria and yeasts to reduce exposure to chemical food contaminants and toxicity’, *Critical Reviews in Food Science and*

Nutrition, 59(10), pp. 1534–1545. doi: 10.1080/10408398.2017.1421521.

Crépet, A. *et al.* (2021) ‘An international probabilistic risk assessment of acute dietary exposure to pesticide residues in relation to codex maximum residue limits for pesticides in food’, *Food Control*, 121. doi: 10.1016/j.foodcont.2020.107563.

Dainelli, D. *et al.* (2008) ‘Active and intelligent food packaging: legal aspects and safety concerns’, *Trends in Food Science and Technology*, 19 (SUPPL. 1), pp. S103–S112. doi: 10.1016/j.tifs.2008.09.011.

Deb, P. (2018) *Environmental Pollution and the burden of Food-Borne Diseases*, *Foodborne Diseases*. Edited by M. A. Holban and A. M. Grumezescu. Elsevier Inc. doi: 10.1016/B978-0-12-811444-5/00014-2.

De Fátima Poças, M. and Hogg, T. (2007) ‘Exposure assessment of chemicals from packaging materials in foods: a review’, *Trends in Food Science and Technology*, 18(4), pp. 219–230. doi: 10.1016/j.tifs.2006.12.008.

Delatour, T. *et al.* (2018) ‘Screening of veterinary drug residues in food by LC-MS/MS. Background and challenges’, *Food Additives and Contaminants – Part A Chemistry, Analysis, Control, Exposure and Risk Assessment*, 35(4), pp. 632–645. doi: 10.1080/19440049.2018.1426890.

Deng, Z. H. *et al.* (2019) ‘Pretreatment techniques and analytical methods for phenolic endocrine disrupting chemicals in food and environmental samples’, *TrAC – Trends in Analytical Chemistry*, 119. doi: 10.1016/j.trac.2019.07.003.

Deshwal, G. K. and Panjagari, N. R. (2020) ‘Review on metal packaging: materials, forms, food applications, safety and recyclability’, *Journal of Food Science and Technology*, 57(7), pp. 2377–2392. doi: 10.1007/s13197-019-04172-z.

Deshwal, G. K., Panjagari, N. R. and Alam, T. (2019) ‘An overview of paper and paper based food packaging materials: health safety and environmental concerns’, *Journal of Food Science and Technology*, 56(10), pp. 4391–4403. doi: 10.1007/s13197-019-03950-z.

De Tandt, E. *et al.* (2021) ‘A recycler’s perspective on the implications of REACH and food contact material (FCM) regulations for the mechanical recycling of FCM plastics’, *Waste Management*, 119, pp. 315–329. doi: 10.1016/j.wasman.2020.10.012.

Edogbo, B. *et al.* (2020) 'Risk analysis of heavy metal contamination in soil, vegetables and fish around Challawa area in Kano State, Nigeria', *Scientific African*, 7, p. e00281. doi: 10.1016/j.sciaf.2020.e00281.

Ernstoff, A. *et al.* (2019) 'Challenges of including human exposure to chemicals in food packaging as a new exposure pathway in life cycle impact assessment', *International Journal of Life Cycle Assessment*, 24(3), pp. 543–552. doi: 10.1007/s11367-018-1569-y.

European Food Safety Authority (2019) 'Scientific support for preparing an EU position in the 51st Session of the Codex Committee on Pesticide Residues (CCPR)', *EFSA Journal*, 17(7). doi: 10.2903/j.efsa.2019.5797.

FAO (2021) – *DDT*. Available at: http://www.fao.org/fao-who-codexalimentarius/codex-texts/dbs/pestres/pesticides/en/ (Accessed: 5 May 2021).

Faustino, M. *et al.* (2019) 'Agro-food byproducts as a new source of natural food additives', *Molecules*, 24(6), pp. 1–23. doi: 10.3390/molecules24061056.

Food, E. and Authority, S. (2011) 'Scientific support for preparing an EU position in the 43rd Session of the Codex Committee on Pesticide Residues (CCPR)', *EFSA Journal*, 9(9), pp. 1–178. doi: 10.2903/j.efsa.2011.2360.

Franco, R., Navarro, G. and Martínez-Pinilla, E. (2019) 'Antioxidants versus food antioxidant additives and food preservatives', *Antioxidants*, 8(11). doi: 10.3390/antiox8110542.

Fred-Ahmadu, O. H. *et al.* (2020) 'Interaction of chemical contaminants with microplastics: Principles and perspectives', *Science of the Total Environment*, 706, p. 135978. doi: 10.1016/j.scitotenv.2019.135978.

Freeman, S. (2018) 'Plastic food contact articles—food chemical safety unwrapped', *Environmental Health Review*, 61(4), pp. 92–97. doi: 10.5864/d2018-028.

Galstyan, V. *et al.* (2018) 'Metal oxide nanostructures in food applications: Quality control and packaging', *Chemosensors*, 6(2), pp. 1–21. doi: 10.3390/chemosensors6020016.

Gaur, N., Narasimhulu, K. and PydiSetty, Y. (2018) ‘Recent advances in the bio-remediation of persistent organic pollutants and its effect on environment’, *Journal of Cleaner Production*, 198, pp. 1602–1631. doi: 10.1016/j.jclepro.2018.07.076.

Geueke, B., Groh, K. and Muncke, J. (2018) ‘Food packaging in the circular economy: Overview of chemical safety aspects for commonly used materials’, in Holban, A. M. and Grumezescu, A. M. (eds) *Journal of Cleaner Production*. Switzerland: Elsevier Ltd, pp. 491–505. doi: 10.1016/j.jclepro.2018.05.005.

Gonzalez Ronquillo, M. and Angeles Hernandez, J. C. (2017) ‘Antibiotic and synthetic growth promoters in animal diets: Review of impact and analytical methods’, *Food Control*, 72, pp. 255–267. doi: 10.1016/j.foodcont.2016.03.001.

Guerreiro, T. M. *et al.* (2018) ‘Migration from plastic packaging into meat’, *Food Research International*, 109, pp. 320–324. doi: 10.1016/j.foodres.2018.04.026.

Guo, W. *et al.* (2019) ‘Persistent organic pollutants in food: Contamination sources, health effects and detection methods’, *International Journal of Environmental Research and Public Health*, 16(22), pp. 10–12. doi: 10.3390/ijerph16224361.

Hahladakis, J. N. *et al.* (2018) ‘An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling’, *Journal of Hazardous Materials*, 344, pp. 179–199. doi: 10.1016/j.jhazmat.2017.10.014.

Hamid, A. A. *et al.* (2012) ‘Composition and bioactivities of Essential Oils View project Food: Its preservatives, additives and applications’, *International Journal of Chemical and Biochemical Sciences*, 1, pp. 36–47. doi: 10.13140/2.1.1623.5208.

Han, J. W. *et al.* (2018) ‘Food Packaging: A Comprehensive Review and Future Trends’, *Comprehensive Reviews in Food Science and Food Safety*, 17(4), pp. 860–877. doi: 10.1111/1541-4337.12343.

Hejna, M. *et al.* (2021) ‘Heavy-metal phytoremediation from livestock wastewater and exploitation of exhausted biomass’, *International Journal of Environmental Research and Public Health*, 18(5), pp. 1–16. doi: 10.3390/ijerph18052239.

Hossain, M. *et al.* (2021) 'Recent trends in the analysis of trace elements in the field of environmental research: A review', *Microchemical Journal*, 165, p. 106086. doi: 10.1016/j.microc.2021.106086.

Hu, Y. and Cheng, H. (2016) 'Health risk from veterinary antimicrobial use in China's food animal production and its reduction', *Environmental Pollution*, 219, pp. 993–997. doi: 10.1016/j.envpol.2016.04.099.

Janjarasskul, T. and Suppakul, P. (2018) 'Active and intelligent packaging: The indication of quality and safety', *Critical Reviews in Food Science and Nutrition*, 58(5), pp. 808–831. doi: 10.1080/10408398.2016.1225278.

Jansen, T. *et al.* (2020) '"All chemical substances are harmful." public appraisal of uncertain risks of food additives and contaminants', *Food and Chemical Toxicology*, 136 (October 2019), p. 110959. doi: 10.1016/j.fct.2019.110959.

Jayant, D. and Halami, P. M. (2020) 'Industrial perspective of food preservatives from microbial origin', in Kataki, R. and Khanal, S. K. (eds) *Current Developments in Biotechnology and Bioengineering*. Elsevier B.V., pp. 243–261. doi: 10.1016/B978-0-444-64309-4.00011-8.

Kamal, A. A. and Fawzia, S. E.-S. (2018) 'Toxicological and safety assessment of tartrazine as a synthetic food additive on health biomarkers: A review', *African Journal of Biotechnology*, 17(6), pp. 139–149. doi: 10.5897/ajb2017.16300.

Kang, H.-S. *et al.* (2018) 'Occurrence of veterinary drug residues in farmed fishery products in South Korea', *Food Control*, 85, pp. 57–65. doi: 10.1016/j.foodcont.2017.09.019.

Kang, Y. *et al.* (2020) 'Health risks and source identification of dietary exposure to indicator polychlorinated biphenyls (PCBs) in Lanzhou, China', *Environmental Geochemistry and Health*, 42(2), pp. 681–692. doi: 10.1007/s10653-019-00402-7.

Karmaus, A. L., Osborn, R. and Krishan, M. (2018) 'Scientific advances and challenges in safety evaluation of food packaging materials: Workshop proceedings', *Regulatory Toxicology and Pharmacology*, 98, pp. 80–87. doi: 10.1016/j.yrtph.2018.07.017.

Khan, I. *et al.* (2019) 'Determination of Major Organophosphate Insecticide Residues in

Cabbage Samples From Different Markets of Dhaka', *Asia Pacific Environmental and Occupational Health Journal*, 5(2), pp. 30–35. Available at: http://www.apeohjournal.org/index.php/v/article/view/92/0.

Khare, S., Tonk A. and Rawat, A. (2018) 'Foodborne diseases outbreak in India: A review', *International Journal of Food Sciences and Nutrition*, 3(2), p. 2. doi: doi.org/10.22271/food.

Khezerlou, A. *et al.* (2020) 'Assessment of Heavy Metal Contamination and the Probabilistic Risk via Salad Vegetable Consumption in Tabriz, Iran', *Biological Trace Element Research*. doi: 10.1007/s12011-020-02365-8.

Kirchhelle, C. (2018) 'Pharming animals: a global history of antibiotics in food production (1935–2017)', *Palgrave Communications*, 4(1). doi: 10.1057/s41599-018-0152-2.

Kosamu, I., Kaonga, C. and Utembe, W. (2020) 'A critical review of the status of pesticide exposure management in Malawi', *International Journal of Environmental Research and Public Health*, 17(18), pp. 1–13. doi: 10.3390/ijerph17186727.

Kumar, M., Chand, R. and Shah, K. (2018) *Mycotoxins and pesticides: Toxicity and applications in food and feed*, *Microbial Biotechnology*. doi: 10.1007/978-981-10-7140-9_11.

Kuppusamy, S. *et al.* (2018) 'Veterinary antibiotics (VAs) contamination as a global agro-ecological issue: A critical view', *Agriculture, Ecosystems and Environment*, 257(January), pp. 47–59. doi: 10.1016/j.agee.2018.01.026.

Liao, H. *et al.* (2018) 'A bibliometric analysis and visualization of medical big data research', *Sustainability (Switzerland)*, 10(1), pp. 1–18. doi: 10.3390/su10010166.

Loganathan, B. G. and Masunaga, S. (2020) *PCBs, dioxins, and furans: human exposure and health effects*, *Handbook of Toxicology of Chemical Warfare Agents*. INC. doi: 10.1016/b978-0-12-819090-6.00018-0.

Majid, I. *et al.* (2018) 'Novel food packaging technologies: Innovations and future prospective', *Journal of the Saudi Society of Agricultural Sciences*, 17(4), pp. 454–462. doi: 10.1016/j.jssas.2016.11.003.

Manage, P. M. (2018) ‘Heavy use of antibiotics in aquaculture: Emerging human and animal health problems – A review’, *Sri Lanka Journal of Aquatic Sciences*, 23(1), p. 13. doi: 10.4038/sljas.v23i1.7543.

Mandlate, J. S. *et al.* (2020) ‘Determination of trace elements in Sergio mirim: an evaluation of sample preparation methods and detection techniques’, *Environmental Science and Pollution Research*, 27(17), pp. 21914–21923. doi: 10.1007/s11356-020-08766-5.

Mania, I. *et al.* (2018) ‘Traceability in the dairy industry in Europe: Theory and practice’, in *Traceability in the Dairy Industry in Europe: Theory and Practice*, pp. 1–160. doi: 10.1007/978-3-030-00446-0.

Margenat, A. *et al.* (2019) ‘Occurrence and human health implications of chemical contaminants in vegetables grown in peri-urban agriculture’, *Environment International*, 124 (July 2018), pp. 49–57. doi: 10.1016/j.envint.2018.12.013.

Marini, M. *et al.* (2021) ‘Daily intake of heavy metals and minerals in food – A case study of four Danish dietary profiles’, *Journal of Cleaner Production*, 280, p. 124279. doi: 10.1016/j.jclepro.2020.124279.

Marriott, N. G., Schilling, M. W. and Gravani, R. B. (2018) ‘Food Contamination Sources’, in. Springer,Cham, pp. 83–91. doi: 10.1007/978-3-319-67166-6_5.

Martins, F. C. O. L., Sentanin, M. A. and De Souza, D. (2019) ‘Analytical methods in food additives determination: Compounds with functional applications’, *Food Chemistry*, 272 (April 2018), pp. 732–750. doi: 10.1016/j.foodchem.2018.08.060.

Massoud, R. *et al.* (2019) ‘Bioremediation of heavy metals in food industry: Application of Saccharomyces cerevisiae’, *Electronic Journal of Biotechnology*, 37, pp. 56–60. doi: 10.1016/j.ejbt.2018.11.003.

Mastromatteo, M. *et al.* (2010) ‘Advances in controlled release devices for food packaging applications’, *Trends in Food Science and Technology*, 21(12), pp. 591–598. doi: 10.1016/j.tifs.2010.07.010.

Mazzoni, M. *et al.* (2018) ‘Trophic transfer of persistent organic pollutants through a pelagic food web: The case of Lake Como (Northern Italy)’, *Science of the Total*

Environment, 640–641, pp. 98–106. doi: 10.1016/j.scitotenv.2018.05.307.

Mehdi, Y. *et al.* (2018) 'Use of antibiotics in broiler production: Global impacts and alternatives', *Animal Nutrition*, 4(2), pp. 170–178. doi: 10.1016/j.aninu.2018.03.002.

Mihaileanu, R. G. *et al.* (2019) 'Assessment of heavy metals (total chromium, lead, and manganese) contamination of residential soil and homegrown vegetables near a former chemical manufacturing facility in Tarnaveni, Romania', *Environmental Monitoring and Assessment*, 191(1). doi: 10.1007/s10661-018-7142-0.

Misihairabgwi, J. M. *et al.* (2019) 'Mycotoxin contamination of foods in Southern Africa: A 10-year review (2007–2016)', *Critical Reviews in Food Science and Nutrition*, 59(1), pp. 43–58. doi: 10.1080/10408398.2017.1357003.

Mohammadzadeh-Aghdash, H. *et al.* (2018) 'Safety assessment of sodium acetate, sodium diacetate and potassium sorbate food additives', *Food Chemistry*, 257 (March), pp. 211–215. doi: 10.1016/j.foodchem.2018.03.020.

Moudgil, P. *et al.* (2018) 'Emerging issue of antibiotic resistance from food producing animals in India: Perspective and legal framework', *Food Reviews International*, 34(5), pp. 447–462. doi: 10.1080/87559129.2017.1326934.

Muncke, J. *et al.* (2020) 'Impacts of food contact chemicals on human health: A consensus statement', *Environmental Health: A Global Access Science Source*, 19(1), pp. 1–12. doi: 10.1186/s12940-020-0572-5.

My, N. H. D., Demont, M. and Verbeke, W. (2021) 'Inclusiveness of consumer access to food safety: Evidence from certified rice in Vietnam', *Global Food Security*, 28(December 2020), p. 100491. doi: 10.1016/j.gfs.2021.100491.

Nasreddine, L. and Parent-Massin, D. (2002) 'Food contamination by metals and pesticides in the European Union. Should we worry?', *Toxicology Letters*, 127(1–3), pp. 29–41. doi: 10.1016/S0378-4274(01)00480-5.

Nerín, C., Aznar, M. and Carrizo, D. (2016) 'Food contamination during food process', *Trends in Food Science and Technology*, 48, pp. 63–68. doi: 10.1016/j.tifs.2015.12.004.

Ng, C. A. and Von Goetz, N. (2017) ‘The global food system as a transport pathway for hazardous chemicals: The missing link between emissions and exposure’, *Environmental Health Perspectives*, 125(1), pp. 1–7. doi: 10.1289/EHP168.

Niu, B. *et al.* (2021) ‘Safety risk assessment and early warning of chemical contamination in vegetable oil’, *Food Control*, 125, p. 107970. doi: 10.1016/j.foodcont.2021.107970.

Njoga, E. O. *et al.* (2018) ‘Assessment of antimicrobial drug administration and antimicrobial residues in food animals in Enugu State, Nigeria’, *Tropical Animal Health and Production*, 50(4), pp. 897–902. doi: 10.1007/s11250-018-1515-9.

Novak, R. (2011) ‘Are pleuromutilin antibiotics finally fit for human use?’, *Annals of the New York Academy of Sciences*, 1241(1), pp. 71–81. doi: 10.1111/j.1749-6632.2011.06219.x.

Oliver, M. *et al.* (2015) ‘What do community health workers have to say about their work, and how can this inform improved programme design? A case study with CHWs within Kenya’, *Global Health Action*, 8(1). doi: 10.3402/gha.v8.27168.

Ortiz-Solà, J. *et al.* (2020) ‘Evaluation of a sanitizing washing step with different chemical disinfectants for the strawberry processing industry’, *International Journal of Food Microbiology*, 334, p. 108810. doi: 10.1016/j.ijfoodmicro.2020.108810.

Pasca, C. *et al.* (2014) ‘Total content of polyphenols and antioxidant activity of different melliferous plants’, *Bulletin UASVM Animal Science and Biotechnologies*, 71(2), pp. 250–255. doi: 10.15835/buasvmcn-asb.

Pilevar, Z. *et al.* (2019) ‘Migration of styrene monomer from polystyrene packaging materials into foods: Characterization and safety evaluation’, *Trends in Food Science and Technology*, 91, pp. 248–261. doi: 10.1016/j.tifs.2019.07.020.

Pius, C. *et al.* (2019) ‘Monitoring polychlorinated dibenzo-p-dioxins/dibenzofurans and dioxin-like polychlorinated biphenyls in Africa since the implementation of the Stockholm Convention—an overview’, *Environmental Science and Pollution Research*, 26(1), pp. 101–113. doi: 10.1007/s11356-018-3629-z.

Rai, P. K. *et al.* (2019) ‘Heavy metals in food crops: Health risks, fate, mechanisms, and management', *Environment International*, 125), pp. 365–385. doi: 10.1016/j.envint.2019.01.067.

Ramos, Ó. L. *et al.* (2018) 'Packaging and Their Effect in Food Quality and Safety', in Grumezescu, A. M. and Holban, A. M. (eds) *Food Packaging and Preservation*. Elsevier Inc., pp. 271–306. doi: 10.1016/B978-0-12-811516-9/00008-7.

Rather, I. A. *et al.* (2017) 'The sources of chemical contaminants in food and their health implications', *Frontiers in Pharmacology*, 8 (November). doi: 10.3389/fphar.2017.00830.

Raymundo-Pereira, P. A. *et al.* (2021) 'Selective and sensitive multiplexed detection of pesticides in food samples using wearable, flexible glove-embedded non-enzymatic sensors', *Chemical Engineering Journal*, 408. doi: 10.1016/j.cej.2020.127279.

Roca-Saavedra, P. *et al.* (2018) 'Food additives, contaminants and other minor components: effects on human gut microbiota – a review', *Journal of Physiology and Biochemistry*, 74(1), pp. 69–83. doi: 10.1007/s13105-017-0564-2.

Rusin, M. *et al.* (2019) 'PCDDs, PCDFs and PCBs in locally produced foods as health risk factors in Silesia Province, Poland', *Ecotoxicology and Environmental Safety*, 172(July 2018), pp. 128–135. doi: 10.1016/j.ecoenv.2019.01.052.

Santarelli, G. A. *et al.* (2018) 'Assessment of pesticide residues and microbial contamination in raw leafy green vegetables marketed in Italy', *Food Control*, 85, pp. 350–358. doi: 10.1016/j.foodcont.2017.09.035.

Scott, A. M. *et al.* (2018) 'Is antimicrobial administration to food animals a direct threat to human health? A rapid systematic review', *International Journal of Antimicrobial Agents*, 52(3), pp. 316–323. doi: 10.1016/j.ijantimicag.2018.04.005.

Setia, R. *et al.* (2021) 'Phytoavailability and human risk assessment of heavy metals in soils and food crops around Sutlej river, India', *Chemosphere*, 263, p. 128321. doi: 10.1016/j.chemosphere.2020.128321.

Sha, J. Bin *et al.* (2018) 'Effects of the long-term consumption of hydrogen-rich water on the antioxidant activity and the gut flora in female juvenile soccer players from Suzhou, China', *Medical Gas Research*, 8(4), pp. 135–143. doi: 10.4103/2045-9912.248263.

Shariatifar, N. *et al.* (2020) 'The concentration and health risk assessment of trace elements in commercial soft drinks from Iran marketed', *International Journal of Environmental Analytical Chemistry*. pp. 1–15. doi: 10.1080/03067319.2020.1784412.

Sharif, M. K., Javed, K. and Nasir, A. (2018) 'Foodborne Illness: Threats and Control', in Holban, M. A. and Grumezescu, A. M. (eds) *Foodborne Diseases*. Elsevier Inc., pp. 501–523. doi: 10.1016/B978-0-12-811444-5.00015-4.

Sharma, A. *et al.* (2019) 'Worldwide pesticide usage and its impacts on ecosystem', *SN Applied Sciences*, 1(11), pp. 1–16. doi: 10.1007/s42452-019-1485-1.

Sivagami, K. *et al.* (2020) 'Antibiotic usage, residues and resistance genes from food animals to human and environment: An Indian scenario', *Journal of Environmental Chemical Engineering*, 8(1), p. 102221. doi: 10.1016/j.jece.2018.02.029.

Sofi, S. A. *et al.* (2018) 'A Comprehensive Review on Antimicrobial Packaging and its Use in Food Packaging', *Current Nutrition & Food Science*, 14(4), pp. 305–312. doi: 10.2174/1573401313666170609095732.

Ssebugere, P. *et al.* (2019) 'Human and environmental exposure to PCDD/Fs and dioxin-like PCBs in Africa: A review', *Chemosphere*, 223, pp. 483–493. doi: 10.1016/j.chemosphere.2019.02.065.

Szűcs, V. *et al.* (2019) 'Modelling of avoidance of food additives: a cross country study', *International Journal of Food Sciences and Nutrition*, 70(8), pp. 1020–1032. doi: 10.1080/09637486.2019.1597837.

Taiwo, A. M. (2019) 'A review of environmental and health effects of organochlorine pesticide residues in Africa', *Chemosphere*, 220, pp. 1126–1140. doi: 10.1016/j.chemosphere.2019.01.001.

Tempelhoff, J. W. N. (2009) 'Civil society and sanitation hydropolitics: A case study of South Africa's Vaal River Barrage', *Physics and Chemistry of the Earth*, 34(3), pp. 164–175. doi: 10.1016/j.pce.2008.06.006.

Tenenbein, M. S. and Tenenbein, M. (2005) ‘Acute pancreatitis due to erythromycin overdose’, *Pediatric Emergency Care*, 21(10), pp. 675–676. doi: 10.1097/01.pec.0000181419.49106.ec.

Thakali, A. and MacRae, J. D. (2021) ‘A review of chemical and microbial contamination in food: What are the threats to a circular food system?’, *Environmental Research*, 194, p. 110635. doi: 10.1016/j.envres.2020.110635.

Thompson, L. A. and Darwish, W. S. (2019) ‘Environmental Chemical Contaminants in Food: Review of a Global Problem’, *Journal of Toxicology*, 2019, pp. 1–14. doi: 10.1155/2019/2345283.

Tudi, M. *et al.* (2021) ‘Agriculture development, pesticide application and its impact on the environment’, *International Journal of Environmental Research and Public Health*, 18(3), pp. 1–24. doi: 10.3390/ijerph18031112.

Van, T. T. H. *et al.* (2020) ‘Antibiotic use in food animals worldwide, with a focus on Africa: Pluses and minuses’, *Journal of Global Antimicrobial Resistance*, 20, pp. 170–177. doi: 10.1016/j.jgar.2019.07.031.

Vipham, J. L. *et al.* (2020) ‘No food security without food safety: Lessons from livestock related research’, *Global Food Security*, 26, p. 100382. doi: 10.1016/j.gfs.2020.100382.

Volschenk, C. M. *et al.* (2019) ‘Bioaccumulation of persistent organic pollutants and their trophic transfer through the food web: Human health risks to the rural communities reliant on fish from South Africa’s largest floodplain’, *Science of the Total Environment*, 685, pp. 1116–1126. doi: 10.1016/j.scitotenv.2019.06.144.

Wang, H. *et al.* (2017) ‘Antibiotic residues in meat, milk and aquatic products in Shanghai and human exposure assessment’, *Food Control*, 80, pp. 217–225. doi: 10.1016/j.foodcont.2017.04.034.

Wang, X. *et al.* (2019) ‘Persistent organic pollutants in the polar regions and the Tibetan Plateau: A review of current knowledge and future prospects’, *Environmental Pollution*, 248, pp. 191–208. doi: 10.1016/j.envpol.2019.01.093.

Xu, Y. *et al.* (2021) 'Metal–organic framework for the extraction and detection of pesticides from food commodities', *Comprehensive Reviews in Food Science and Food Safety*, 20(1), pp. 1009–1035. doi: 10.1111/1541-4337.12675.

Yapp, C. and Fairman, R. (2006) 'Factors affecting food safety compliance within small and medium-sized enterprises: Implications for regulatory and enforcement strategies', *Food Control*, 17(1), pp. 42–51. doi: 10.1016/j.foodcont.2004.08.007.

Yu, Z. *et al.* (2020) 'Smart traceability for food safety', *Critical Reviews in Food Science and Nutrition*, 0(0), pp. 1–12. doi: 10.1080/10408398.2020.1830262.

Yucel, U. (2016) 'Intelligent packaging', in Yucel, U. (ed.) *Food, Cosmetics and Drug Packaging*. Manhattan: Elsevier, p. 7. doi: 10.1201/b11204-46.

Zhao, L. *et al.* (2018) 'Multi-class multi-residue analysis of veterinary drugs in meat using enhanced matrix removal lipid cleanup and liquid chromatography-tandem mass spectrometry', *Journal of Chromatography A*, 1549, pp. 14–24. doi: 10.1016/j.chroma.2018.03.033.

Zhong, Y. *et al.* (2018) 'Effects of food-additive-information on consumers' willingness to accept food with additives', *International Journal of Environmental Research and Public Health*, 15(11). doi: 10.3390/ijerph15112394.

Zikankuba, V. L. *et al.* (2019) 'Pesticide regulations and their malpractice implications on food and environment safety', *Cogent Food & Agriculture*, 5(1). doi: 10.1080/23311932.2019.1601544.

CHAPTER 6: THE ENVIRONMENTAL IMPACT OF MUNICIPAL SOLID WASTE AND THE APPLICATION OF BIOSURFACTANTS IN THE BIOREMEDIATION OF POLLUTED ENVIRONMENTS

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Abstract

Municipal solid waste (MSW) has been on the global sustainable development agenda in recent years due to its global economic impact. Not only is it a financial burden; the nature of pollutants from the waste is far-reaching and causes adverse effects on human health and the environment at large. The compounded challenges caused by MSW is exacerbated by rapid population growth in urban centres and the lack of low-cost remediation techniques. Essentially, this growth increases the waste generation output and puts a strain on the limited resources. Researchers have identified the socio-economic repercussions and opportunities in managing MSW. However, the effectiveness of the proposed strategic recommendations on waste control depends on partnerships between local governments and the private sector's technical skills. Technologies such as the use of biosurfactants as a bioremediation strategy for polluted environments and relatively low-cost techniques such as landfilling have been explored, but the usage of either strategy depends on financial and land availability factors in most countries. Moreover, these technologies are meant to minimise exposure to toxic and other hazardous materials to acceptable levels, especially in susceptible populations in light of sustainable development and global pledge on causing least harm to the environment, municipalities are starting to invest in environmental management systems and bioremediation processes to treat contaminated environments.

Keywords: Municipal solid waste, biosurfactants, sustainable development, bioremediation, environmental health, environmental sustainability

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6.1. Introduction

Environmental degradation is a worldwide reality in light of the global agenda on sustainable development and sustainable world economies. Various environmental factors affect the realisation of global pledges such as vision 2030 on sustainable development adversely. Municipal Solid Waste (MSW) in both developed and low-income countries poses a serious threat to environmental integrity and human health (Beyerlin and Marauhn, 2011). The nature of pollutants resulting from the management or mismanagement of MSW has negative repercussions not only on the local economy but on a larger scale, with catastrophic influence on climate change (Mazzi *et al.*, 2016). The negative consequences of MSW have prompted a considerable amount of published studies globally (Vallero and Shulman, 2019, Shar et al., 2016, Dhokhikah et al., 2015). These studies have largely focused on technologies used to render municipal solid-waste services and factors influencing the output of waste in communities. Nevertheless, extensive research has not been done on the larger-scale application of biosurfactants in municipal solid-waste management.

Biosurfactants are globally acclaimed green alternative substances applied widely in different industries. They are biodegradable, highly stable, and have a low environmental impact (Olasanmi and Thring, 2018) and are nontoxic by nature (Shar *et al.*, 2016). On the contrary, other forms of surfactants are are non-biodegradable and have toxic capabilities. These surfactants are largely derived from synthetic petroleum feedstock. There has been a rise in the application of biosurfactants in the bioremediation of polluted environments. Most notably, polluted environments by municipal solid waste have been documented to cause severe degradation and aesthetic problems in affected communities. In recent years, biosurfactants have gained industry endorsements due to their ability to withstand extreme temperatures and remain effective (Varjani and Upasani, 2017; Massoud *et al.*, 2019). Moreover, researchers further note their benefits such as increased biodegradability, high specificity in detoxifying pollutants and efficiency in extremes of salinity and pH (Shar *et al.*, 2016; Maikudi Usman *et al.*, 2016; (National Department of Health, 2004).

Surfactants generally have vast applications in different industries. The synthetic surfactants used in the recovery of heavy metals after incineration can cause secondary pollution to the environment because they are not biodegradable. This has led to the rise in the application of non-toxic biosurfactants (Xu and Chen, 2015; Liu *et al.*, 2017). Experiments have been conducted to test the toxicity of fly ash after incineration through the application of biosurfactant Saponin and chelator solution. Xu and Chen (2015) discovered a decrease in the toxicity levels in relation to the concentration level of heavy metals before the application. This shows the effectiveness of saponin biosurfactant in bioremediation of polluted environments. These kinds of research require more funding to ascertain the applicability of methods on a larger scale and recruit a multidisciplinary team to evaluate the appropriateness of the technology further.

Municipal solid-waste management (MSWM) is a complex subject and it encompasses concepts from various disciplines. This is evident in the stakeholders required to uphold the responsibility of rendering waste management services. A strong component of municipal solid-waste management comprises a multi-skilled team (Dhokhikah et al., 2015). Therefore, the key stakeholders can be divided into the following disciplines: engineering, public health, economics, technical labour, community volunteers and marketing. This is by no means an exhaustive list; however, there is a general consensus that a combination of various skill sets in the mentioned disciplines is perceived to be a comprehensive and efficient strategy each municipality must possess to ensure effective service delivery. Other fields of interest should include microbiology and toxicology. These mentioned disciplines can add value, more especially when technologies such as the use of biosurfactants are introduced. The misapplication and improper handling of these technological products can have adverse health and environmental effects.

More recently, there have been debates about the appropriateness of the technologies currently used in some countries. The most common example of such technologies is the use of incinerators and landfills. Among other emerging technologies is the use of biosurfactants in the bioremediation of contaminated environments by municipal waste. These options have advantages and disadvantages pertaining to cost-effectiveness and potential pollution control. However, different nations prefer one method over the other or a combination of the three, depending on geographical location, economic viability, availability of human resources, current policies and environmental laws. Some scholars argue that there have not been technological advancements in some countries to deal with the changing profile of the waste (Vallero and Shulman, 2019). Furthermore, they assert that the waste currently produced differs from past decades, both in volume and material composites.

As was pointed out in the preceding paragraphs, MSWM is multifaceted. This has led to the recognition that the involvement of stakeholders such as the informal sector should be explored to alleviate the burden of waste collection and management in municipalities (Weng and Fujiwara, 2011; Aleluia and Ferrão, 2016; Ma and Hipel, 2016; Aparcana, 2017; Hettiarachchi, Meegoda and Ryu, 2018). Moreover, various studies have shown a decline in solid-waste pile-up in countries where informal reclaimers operate with liberty (Aparcana, 2017). To further support the use of stakeholders, the expertise of private companies is highly recommended, due to the technical skills they offer and the potentially low cost of their services.

6.2. Municipal solid-waste trends

Municipal solid-waste management has been among the key global concerns in recent years. The impact of waste is undeniably due to the evident consequences in municipalities across the world. A large volume of published studies (Gu *et al.*, 2015; Guerrini *et al.*, 2017; Vallero and Shulman, 2019) describes the impact of waste in municipalities, both in emerging economies and established nations. According to Leal Filho (*et al.*, 2016), the quantity of municipal waste generated globally is between 1.3 and 1.9 billion tonnes per year. Furthermore, it is estimated to increase to approximately 2.2 billion tonnes per annum by the year 2025. This could be attributed to increased food production and projected population growth. This suggests a link between the increase in population numbers and the waste output.

Municipalities or local authorities are entrusted with the provision of basic services such as water and sanitation services and solid-waste management (Kawai and Tasaki, 2016; Vallero, 2019). Additionally, the municipality must control, collect, process, utilize and dispose of the waste efficiently and sustainably. This is to ensure that minimal nuisances are caused and the health of the public is protected (Zhang, Huang and He, 2014; Vallero, 2019). Therefore, municipal solid-waste management systems require multi-processes to curb the impact of resultant nuisances. The biggest challenge in managing waste is observed in low and middle-income countries, which may have the desired systems, but operate at low standards, with minimal implementation capacity (Aparcana, 2017; Kasinja and Tilley, 2018).

The delivery of hygiene and refuse collection services is an imperative, yet challenging matter in the rapidly growing cities of developing countries. Vallero (2019) has duly noted that a city that cannot manage its waste efficiently will rarely succeed in the management of other multifaceted services such as education, health and transportation. These have significant human health and environmental implications (Abubakar, 2017). Uncollected garbage has detrimental environmental consequences in most local authorities. This is true, especially in areas where the roads are not accessible for waste collection; consequently, a deterioration in the aesthetics of the city is evident. Therefore, uncollected or improperly managed solid waste reduces the visual quality of the environment and causes health and safety risks in communities (Ablo and Yekple, 2018). Improper waste disposal has resulted in poor hygiene and a lack of access to clean water and sanitation in the cities, particularly among the urban poor (Kawai and Tasaki, 2016; Ablo and Yekple, 2018). Although access to toilets is normally higher in cities than in rural areas, unhygienic conditions for poor people in urban areas are intensified by high-density living, insufficient septage, poor drainage and solid waste management (SWM).

Solid-waste management has become a significant issue for developing nations. Quickly expanding populace, poor waste services, higher life-standards (economic development and urbanization rates) and innovative progressions consistently increase the amount and variety of solid waste. This leads to large amounts of waste being illegally dumped, burnt or disposed of at landfills (Mohammed *et al.*, 2017; Coban, Ertis and Cavdaroglu, 2018). In such a complicated environment, municipal authorities need to develop effective ways of dealing with the consistently rising metropolitan solid waste using unconventional waste minimization and remediation methods (Coban *et al.*, 2018).

Municipal solid-waste management (MSWM) does not only depend on technological innovation. It needs an integration of several factors and the influence of social, economic and psychological dynamics such as policy and public participation, including behaviour and attitude (Ma and Hipel, 2016). Municipal solid-waste management consists of several activities, including collection, transportation, treatment, material and energy recovery, and disposal. Therefore, municipal solid-waste collection can be operated in several ways. The methods of waste collection can be summarised as follows: drop-off (bring) collection, door-to-door collection and mixed systems that are often adopted (Seyring *et al.*, 2016; Letcher and Slack, 2019). This shows that there is no unique method that is used globally, but each local authority has a preference. Likewise, with remediation technologies, each country is bound to use what works and is cost effective.

Municipal solid waste is largely influenced by several factors. According to Al-Jarallah and Aleisa (2014), these significant factors are geographical location, climatic conditions, population and sociocultural properties. Essentially, poorer countries are reported to have low waste-generation capabilities per capita per day compared to their high-earning counterparts. This observation can be attributed to development and buying power of consumers in developed nations. Another observation is the waste type generated by these contrasting nations of different social standing; the waste in developing nations is predominantly biodegradable, whilst developed countries have large quantities of recyclable waste. This provides opportunities for developed nations to consider alternative remediation strategies or, alternatively, revise the existing methods. The large quantities of biodegradable waste can then be re-purposed through the use of biosurfactants.

6.3. The informal solid waste management

In the municipal solid-waste management chain there are a role-players whose contribution may be less visible due to stigma, relevance and other socio-economic factors. The informal sector contributes significantly to the collection and distribution of waste, especially in low-income countries. This contribution has both pros and cons. Globally, scrap dealers and rag pickers, also known as informal waste reclaimers, have an influence on the type of municipal solid waste found in underdeveloped countries, as shown in Figures 6.1, 6.2 and 6.3. These informal traders play a vital role in the value chain by reprocessing the waste into secondary raw material according to Leal Filho *et al.* (2016). Moreover, they are known to contribute significantly to recycling activities, thus reducing the volume of waste deposited in landfill sites, especially in low- and middle-income countries (Aparcana, 2017). This is supported by research conducted in rural Asia, where it was shown that there is a positive relationship between wealth creation and the generation of municipal waste. The more wealth generation initiatives were initiated, a decrease in organic waste was noted across developing Asian countries (Aleluia and Ferrão, 2016). By implication, a revised strategy where the informal sector is complemented with the application of biosurfactants in municipal solid-waste reduction and remediation could be a breakthrough in waste management.

Figure 6.1: Non-biodegradable waste collected by the informal sector, South African township. Picture captured by Lebelo at Duduza township, Gauteng, South Africa.

Figure 6.2: Recyclable waste collected by the informal sector awaiting transportation to the recycling plant by the third-party waste collector. Picture captured by Lebelo at Duduza township, Gauteng, South Africa.

Figure 6.3: Alcoholic beverage bottles collected from local entertainment areas. Picture captured by Lebelo at Duduza township, Gauteng, South Africa.

In light of the emergence of a new socioeconomic window of opportunity for waste management, policy and decision-makers have been exploring the possibility of recognising the waste-management informal sector. The informal waste sector consists of individuals, groups and microenterprises that render informal waste services (Aparcana, 2017). Generally, this sector is not recognised or even allowed by authorities to operate. Contrary to the authority's resistance, it is reported that in countries such as Mali, 100% of all recycling activities are carried out by the informal sector. Aparcana (2017) explored whether the informal sector can be formalised through policymakers gaining traction on the idea of including them in the management initiatives and activities. The long-term effects of such an intervention are not known; however, increased involvement and support from stakeholders can be a stepping stone towards the success of the formalization process (Aleluia and Ferrão, 2016).

6.4. Comparison between developed and low-middle-income countries

It was discovered that one out of two poor people in Cameroon does not have access to basic amenities such as basic sanitation, health and waste-collection services (Parrot, Sotamenou and Dia, 2009). This problem is further fuelled by overpopulation in urban centres, where municipalities are battling with funds and equipment to render effective municipal solid-waste services. There is a potential negative loop in this context, when people flock to urban areas and the amount of municipal waste generated increases, thus overwhelming the limited resources available in municipalities. This results in declining service delivery and the accumulation of waste.

The causal-loop concept is best described using the following scenario: A new chain of factories and property developments are initiated in a local municipality close to a city centre. The anticipation of employment opportunities and better living standards prompts more people from nearby towns to flock to the urban areas (Al-Jarallah and Aleisa, 2014; Leal Filho *et al.*, 2016). As a result, food consumption and waste generation sharply increase, thus creating a demand for sufficient waste-management services (Parrot *et al.*, 2009; Gu *et al.*, 2015). This creates a problem for the municipality, taking into consideration the resource-intensive nature of providing waste-management services and the remediation of polluted land by municipal solid waste. This is in light of the manpower and waste-collection vehicles, along with the capacity to render such services on a consistent basis (Aboyeji and Eigbokhan, 2016). If the municipality devises a plan to steer the people from the urban centres, it can lower the percentage of waste generated and complaints that may arise due to poor service delivery (Guerrini *et al.*, 2017). Ultimately, the municipality will not need to purchase more waste-collection vehicles and invest heavily in remediation technologies. Thus, further investment on service delivery and capacity will be eliminated. Therefore, the causal-loop analysis and understanding can assist service delivery-intensive organisations in designing systems and understanding system dynamics.

In a study conducted in Cameroon, it was revealed that the majority of the infrastructure is located in urban centres. However, there are fewer bins or garbage bins at the peri-urban areas. One of the major challenges is the mushrooming of illegal dumping as a result of domestic waste pile-up (Parrot *et al.*, 2009; Al-Jarallah and Aleisa, 2014; Zhang *et al.*, 2014). As it stands, poorer countries do not have the capacity to apply biomolecule remediation techniques to treat the municipal waste before final disposal. This is evident in the pile-up of waste. Figures 6.4 and 6.5 show the general conditions associated with waste pile-up due to an array of factors such as delayed waste collection or lack of waste-disposal facilities. In rural Malawi, it was found that those who do not dump waste by the roadside usually have a dug pit in their plots as a solid-waste management strategy (Kasinja and Tilley, 2018). Extensive literature review on municipal solid-waste management points out that several variables influence the cost of waste collection. As noted by Guerrini *et al.* (2017), the variables are population features, which include tourist flow, density, age and size; geographical characteristics that affect the nature of vehicles; quantity of waste generated, which influences the manpower required; and the method of collection, which could be resource intensive.

Figure 6.4: Illegal dumping spots by the roadside and vacant land that require bioremediation. Picture captured by Lebelo at Motlhasedi village township, Limpopo, South Africa.

Figure 6.5: Municipal solid-waste piles ready to be collected by municipal solid-waste vehicles. Picture captured by Lebelo at Joe Slovo township, Free State, South Africa.

The distances between the house and garbage are perceived as one of the contributing factors to waste-disposal behaviour. Notably, the further the garbage bin from the house, the more likely people are to dump waste on sidewalks and open spaces. The poor state of repair pertaining to municipal waste-management vehicles and migration are the most common factors exacerbating the challenges in sub-Saharan countries (Kasinja and Tilley, 2018). Moreover, most countries depend on assistance from non-governmental organisations to alleviate the burden of MSW collection.

The pharmaceutical waste in the form of medicine and pills generated by households poses health hazards to people working in landfills or anyone exposed to the waste. It is classified as part of hazardous household waste due to its risk rating and potential effects (Letcher and Slack, 2019). The waste should never be mixed with normal domestic waste due to its high-risk factor. Pharmaceutical residue causes environmental pollution and contributes to antibiotic resistance, thus interfering with the hormonal system (Jonjić and Vitale, 2014). Current practice in Croatia encourages local pharmacies to take sealed waste containers from households to assist the government with the burden of segregating and disposing of waste in an approved way.

The ‘proximity principle’ has been adopted by the European Union in their environmental and waste-management policies. The principle essentially states that the waste should managed close to its source (Okuda and Thomson, 2007). However, this raises challenges regarding capacity. In most African countries, there is capacity in terms of landfills, which are a preferred method, compared to incineration and bioremediation. In contrast, Asian countries such as Japan do not have the space required for landfill operations. As a result, incineration is preferred, because the waste will be managed close to the source (Okuda and Thomson, 2007). Both incineration and landfilling have benefits; however, there are secondary pollutant exposures linked with the use of either technology. It is suggested that either method of remediation be partnered with the use of biosurfactant for optimal benefits. Studies show that the use of biosurfactants can reduce the toxicity of heavy metals from incineration by-products and facilitate the decomposition process in landfill sites (Shao *et al.*, 2017).

Worku (2016) argues that the volume of waste in the city of Tshwane, South Africa, can be attributed to the utilisation of obsolete technological methods and the inability to enforce municipal by-laws. The author further asserts that the municipality is reluctant to partner with private companies to assist with waste management, despite the capacity they possess regarding technologically advanced equipment. A study was conducted to assess which service is the best between public provision of MSW and contracting or outsourcing. This study revealed that using the private sector had benefits in terms of lower production costs, compared to the public sector. However, the researchers note that this method is efficient in large municipalities where great cost savings can be achieved (Pérez-López *et al.*, 2016). The use of biosurfactants generally lowers costs, compared to landfilling and incineration; however, methods of mass production at low cost are yet to be developed. For this reason, it is a challenge for municipalities to fully commit to using biological means in treating their waste and remediating polluted environments. To alleviate the burden of MSW management, it is recommended that businesses be incentivised for managing waste properly.

In light of the 2030 agenda by the United Nations (UN), issues of sustainability have been raised due to the impact of MSW globally. Sustainability has been reported to have at least three central pillars; the environment, economy and society (Hettiarachchi *et al.*, 2018). These pillars are addressed in depth in the Sustainable Development Goals (SDGs), together with the potential impact of most anthropogenic developments. This has initiated interventions such as the ‘buy-back’ programmes. These programmes fundamentally encourage consumers and large corporations to reclaim bottles, glass, aluminium materials, etc., to recover deposits that were paid upfront. However, these programmes have been questioned regarding the inclusion of food waste since it constitutes a significant portion of municipal waste. Moreover, researchers agree that food waste creates a nuisance, thus making it unmanageable, especially in low-income countries. Technologies such as bioremediation can prove to be effective in remediating food waste. Under favourable conditions, microbial action can break down the food into compost and other renewable energy sources.

6.5. Effects of urbanisation on waste generation

In order for any integrated solid-waste management system (ISWMS) to be effective, waste must be characterised. This works by reducing the ever-escalating amount of municipal solid waste (Abbasi and El Hanandeh, 2016; Pérez-López *et al.*, 2016; Seyring *et al.*, 2016). In addition to the ever-increasing waste, there is an observed correlation between income and waste generation. Essentially, the higher the income, the more waste is generated. This supports the theory that urbanisation is one of the factors heavily involved in municipal solid-waste generation, due to the influx of people in urban areas seeking for employment opportunities (Al-Jarallah and Aleisa, 2014; Leal Filho *et al.*, 2016). It is imperative to note that the ISWMS often requires the consideration of different levels of management. As shown in Figure 6.6, decisions taken before devising an efficient ISWM strategy should undergo a rigorous consultation processes. Basically, the application of biosurfactants as a bioremediation tool will have both environmental and economic benefits, provided top managers are on board and relevant stakeholders have been consulted.

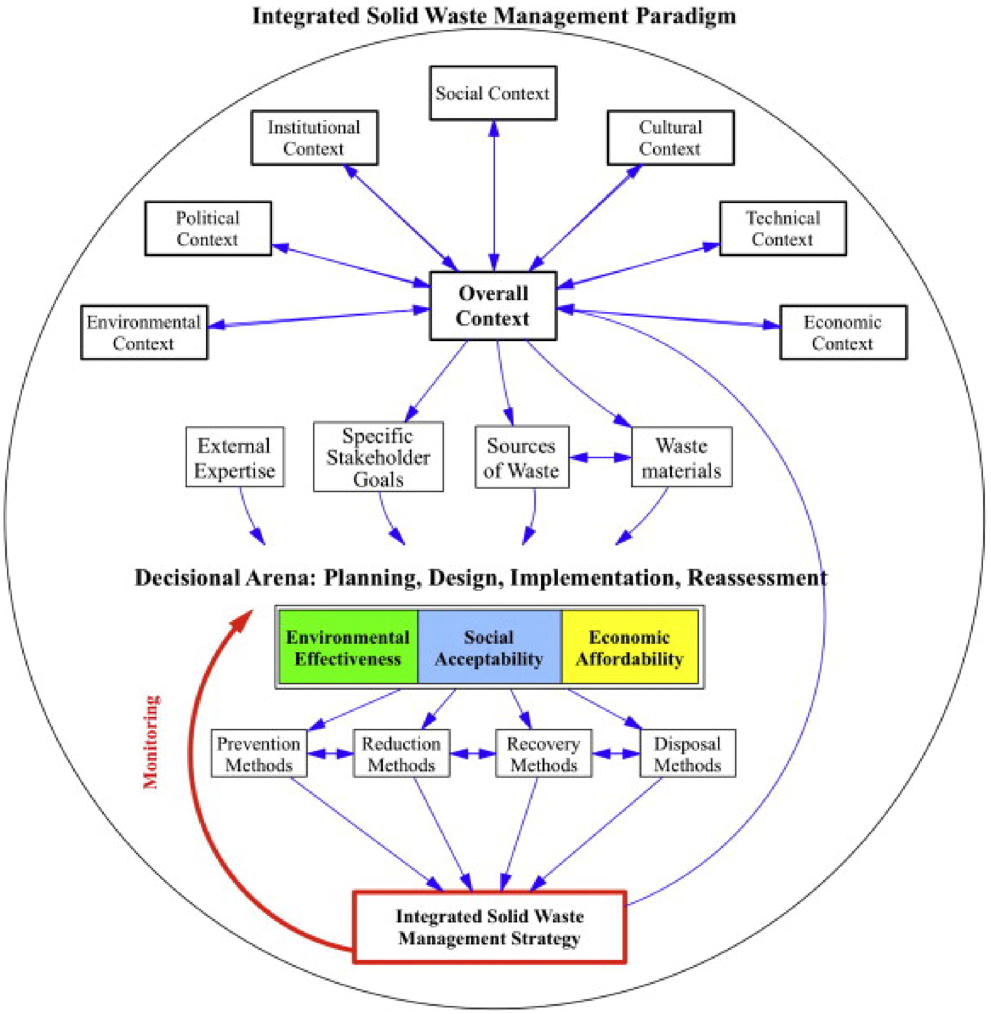


Figure 6.6: Integrated solid-waste management illustration showing the relationship between the stakeholders components that promoted effective waste management (Adapted from Marshall and Farahbakhsh, 2013).

A few positives have been noted regarding the increasing waste generation in the populated urban centres. In England, recycling activities have been introduced through structured interventions in the form of policies and waste minimisation programmes, thus reducing the MSW by 12% in 2012 (Weng and Fujiwara, 2011; Seyring *et al.*, 2016). Other strategies to control the increase in waste generation is to conduct characterization, which is commonly done using three key areas, namely waste product analysis, market analysis and direct sampling. It can further be supplemented by using predictive models to forecast the amount of waste to be generated in a given month (Abbasi and El Hanandeh, 2016).

6.6. Public health nuisances and safety

The informal waste sector has advantages; however, there are barriers underlying operations and management within this sector. As stated by Aparcana (2017), there are issues of health, safety and security in the informal sector. Most of the problems can be attributed to the socio-economic nature of the operations. Various studies have identified social problems such as poor working conditions amongst vulnerable groups, child exploitation through labour, thus resulting in absenteeism from school and low education levels in adults (Zolnikov *et al.*, 2018). Informal waste picking has been documented to facilitate health complications in the form of disease and occupational injuries through unsafe work practices.

Informal-sector workers can be exposed to the following conditions and diseases: musculoskeletal conditions, exposure to sharp objects resulting in a needle prick causing Hepatitis B and C, dog bites, gastrointestinal problems, social exclusion, marginalisation and rejection (Kawai and Tasaki, 2016; Ma and Hipel, 2016). Figure 6.7 shows how the informal-sector workers can cause a nuisance and change the character and aesthetics of the area if they are not properly managed and controlled.

Figure 6.7: Solid waste collected by informal reclaimers causing a public health nuisance in the City of Ekurhuleni municipality, South Africa. Picture captured by Lebelo at Tsakane township, Gauteng, South Africa.

The same fate of adverse exposure is also suffered by municipal solid-waste management workers who manually load the waste into waste-collection vehicles and sweep the streets in the form of dust, bioaerosols, foul odours and noise levels that are detrimental to their health (Jayakrishnan, Jeeja and Bhaskar, 2013; Ncube, Ncube and Voyi, 2017).

Generally under warm, moist conditions, organic waste becomes an ideal breeding ground for disease-causing organisms. Pathogens such as bacteria, viruses, protozoa, fungi and worms may have easy access to the waste through vectors (Costa, Alfaia and Campos, 2019). These are all organic components that would make the usage of biomolecules effective in remediating polluted areas. In municipal waste, the typical carriers of disease such water, air and food are not too significant. The principal sources are mosquitoes, flies and rodents, as shown in Figure 6.8. There has been sufficient evidence showing the relationship between municipal solid waste and disease. Therefore, the protection of public health requires constant vigil.

Figure 6.8: Growing rodents found under municipal solid-waste piles. Picture captured by Lebelo at Duduza township, South Africa.

6.7. Human health & environmental effects

Landfill sites are not properly designed and the upkeep is usually not satisfactory (Al-Jarallah and Aleisa, 2014). This is further supported by the works of Parrot and his colleagues, who note that improper MSW management directly affects environmental sanitation (Parrot *et al.*, 2009; Guerrini *et al.*, 2017). Furthermore, studies have shown a positive relationship between disease manifestation, respiratory complications and the accumulation of waste, especially in the informal sector where waste reclaimers thrive.

Recent studies show the relationship between gases released into the atmosphere by landfill sites and the health consequences thereof. Yu *et al.* (2018) state that a significant number of the studies have focused on high-level exposure levels of chemicals, rather than on lower-level multi-pollutant exposures, as denoted in Table 6.1. In addition, they report that lower-level multi-pollutant exposure studies have mainly been inconclusive or contradictory. Landfills are known to release particulate matter with aerodynamic diameter <10 µm and gases such as hydrogen sulphide (H_2S) and ammonia (NH_3). Moreover, children have been reported to be the affected the most by ambient air pollution caused by landfill sites, especially in communities in the vicinity of the landfill site (Yu *et al.*, 2018). Moreover, their study was to measure the effect of ambient air pollution from landfill sites on children's respiratory health and non-specific immunity. In China, Yu and colleagues detected air pollutants such as methane, nitrogen dioxide, sulphur dioxide, ammonia, carbon monoxide sulfurated hydrogen, odour and particulate matter. Upon testing the lung functions of the children, symptoms were significantly different between the exposed and the non-exposed group ($P<0.05$), thus confirming the relationship between the vicinity of the landfill and the children's lung health. However, it is recommended that longitudinal studies be conducted to elucidate the interaction between landfill gases and other environmental factors on respiratory symptoms. This shows the vulnerability of certain groups, especially children, in low-income countries (Ma and Hipel, 2016).

Table 6.1: Summary of factors, risks and hazard exposures associated with people working in informal waste collections site (Adapted from Jayakrishnan et al., 2013; Abbasi and El Hanandeh, 2016).

Physical	Chemical	Biological	Mechanical	Ergonomic risks factors	Social factors
Heat/Cold	Oils/grease	Bacteria	Fractures	Weightlifting	Low pay
Pressure	Pesticides	Viruses	Trips and falls	Excessive work rhythm	Hazardous worksites
Humidity	Herbicides	Fungi	Run over by trucks/accidents	Monotony	Lack of rights
Ionizing/Nonionizing radiation	Cosmetics	Parasites	Crushed limbs	Inappropriate posture	Lack of training
Vibrations	Medicine	Worms	Punctures from sharp objects	Hand-intensive work	Lack of healthcare
Vapour, gas and dust	Battery acids	Toxins	Entrapment	Work stress	Lack of vocational opportunities

6.8. Waste control strategies and the use of biosurfactants in bioremediation

Municipal solid waste generally consists of garden refuse, domestic waste, commercial waste, industrial waste, and construction and demolition waste. In Suzhou China, the largest contributor of domestic waste is food waste (65.7%), followed by paper (14.3%) and plastic (8.9%) (Gu *et al.*, 2015). These are the most significant figures in the study, showing how plastic waste generation has been reduced due to the user-fee policy, which requires of users to make additional payments for plastic. This policy is adopted by many nations in both developed and developing countries. A study in Indonesia, which had similar traits, discovered that 64.19 % and 10.79 % of waste are contributed by food waste and plastic, respectively (Dhokhikah *et al.*, 2015). The two studies show a similar trend where food and plastic constitute a large portion of the waste.

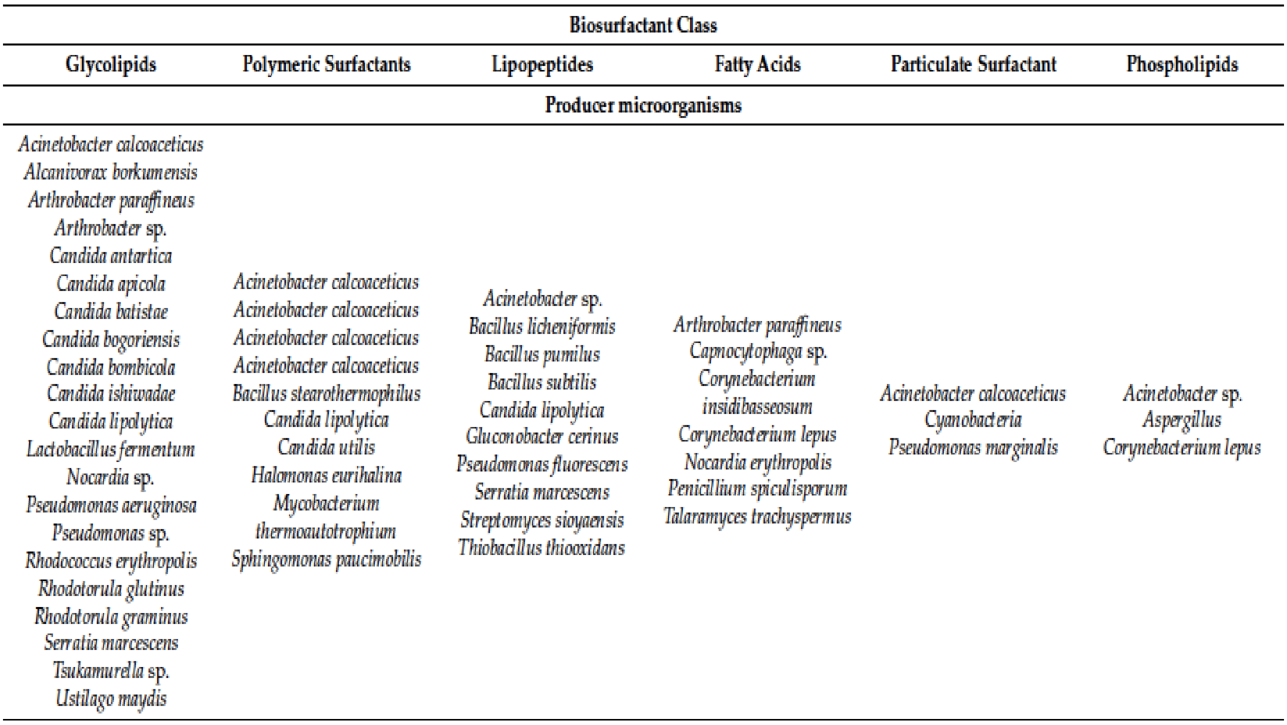
A waste control hierarchy has been developed in past years, though most countries cannot fully achieve all the requirements. Filho *et al.* (2016) simplifies this hierarchy in the following order: waste prevention (Oelofse, Muswema and Ramukhwatho, 2018), followed by waste minimization and reuse if there is any waste. If the waste cannot be reused it must be recycled or turned into compost by different bioremediation techniques or the use of eco-friendly chemicals to facilitate the process. When further processing is not possible, the waste can be used for energy recovery through incineration and lastly landfilling, which is a non-desirable option (Zurbrügg *et al.*, 2012). However, municipal waste at a landfill site can still be treated biologically using biosurfactants, which have been growing in reputation and vast application.

Developing nations usually benchmark with established countries regarding best practices and bureaucratic processes. This is often problematic during policy adoption and implementation. Usually, these policies do not fit the context on developing nations, thus creating a financial strain on the government (Aparcana, 2017; Yu *et al.*, 2018). Pieces of legislation have been proposed by the European Union (EU) to regulate the waste sector; thus encouraging recycling activities and moving away from landfill disposal (Letcher and Slack, 2019). The central ideas in these policies are to improve taxes and tariffs, possibly through increased debt-collection services and tariff reviews. Secondly, outsource further funds and resources from banks and private investors, which will ultimately increase the already existing debt. Thirdly, the efficiency of service delivery is improved, which is the most desirable regarding maintaining quality standards (Guerrini *et al.*, 2017).

6.9. Applications of biosurfactants in municipal solid waste

Biosurfactants are structurally classified into the following major groups: Glycolipids, Liposaccharides, Lipopeptidides (Shar *et al.,* 2016), Phospholipids, Fatty acids (Maikudi Usman *et al.*, 2016), lipoproteins and polymeric and particulate surfactants (Shar *et al.*, 2016; Olasanmi and Thring, 2018). The most common types of biosurfactants are Glycolipids, which consist of rhamnose, mannose, glucuronic acid, disaccharides, monosaccharides, galactose, etc. (Maikudi Usman *et al.*, 2016).

Table 6.2: Main classes of biosurfactants and respective producing microorganisms (Santos *et al.*, 2016) Open access.



Biosurfactant Class					
Glycolipids	**Polymeric Surfactants**	**Lipopeptides**	**Fatty Acids**	**Particulate Surfactant**	**Phospholipids**
Producer microorganisms					
Acinetobacter calcoaceticus *Alcanivorax borkumensis* *Arthrobacter paraffineus* *Arthrobacter* sp. *Candida antartica* *Candida apicola* *Candida batistae* *Candida bogoriensis* *Candida bombicola* *Candida ishiwadae* *Candida lipolytica* *Lactobacillus fermentum* *Nocardia* sp. *Pseudomonas aeruginosa* *Pseudomonas* sp. *Rhodococcus erythropolis* *Rhodotorula glutinus* *Rhodotorula graminus* *Serratia marcescens* *Tsukamurella* sp. *Ustilago maydis*	*Acinetobacter calcoaceticus* *Acinetobacter calcoaceticus* *Acinetobacter calcoaceticus* *Acinetobacter calcoaceticus* *Bacillus stearothermophilus* *Candida lipolytica* *Candida utilis* *Halomonas eurihalina* *Mycobacterium thermoautotrophium* *Sphingomonas paucimobilis*	*Acinetobacter* sp. *Bacillus licheniformis* *Bacillus pumilus* *Bacillus subtilis* *Candida lipolytica* *Gluconobacter cerinus* *Pseudomonas fluorescens* *Serratia marcescens* *Streptomyces sioyaensis* *Thiobacillus thiooxidans*	*Arthrobacter paraffineus* *Capnocytophaga* sp. *Corynebacterium insidibasseosum* *Corynebacterium lepus* *Nocardia erythropolis* *Penicillium spiculisporum* *Talaramyces trachyspermus*	*Acinetobacter calcoaceticus* *Cyanobacteria* *Pseudomonas marginalis*	*Acinetobacter* sp. *Aspergillus* *Corynebacterium lepus*

Various authors have documented the uses of biosurfactants in several publications. Biosurfactants are used for the following roles: removal of pesticides (Shar *et al.*, 2016), cleaning and sanitising, emulsification (Varjani and Upasani, 2017), surface tension reduction, dispersal, solubilisation, wetting, foaming (Olasanmi and Thring, 2018), facilitation of biocontrol of microbes (Shar *et al.*, 2016), etc. Biosurfactant production is influenced by a variety of environmental factors. Maikudi Usman *et al.* (2016) and colleagues affirm that the quality, quantity and the nature of biosurfactant produced is influenced by the concentration of elements such as iron, phosphorus ions, nitrogen, etc. Moreover, environmental factors such as dilution rate, pH, temperature and agitation also play a significant role in the production of biosurfactants.

The literature describes surfactants as active compounds that have both hydrophilic and hydrophobic properties (Sáenz-Marta *et al.*, 2015; Sarubbo *et al.*, 2015; Shar *et al.*, 2016; Santos *et al.*, 2016). Essentially, they have surface tension-reducing qualities between a plethora of substances, i.e., gases, solids and liquids. Surfactants often used in remediation generally enhance the removal of pollutants by increasing their solubility and bioavailability (Shao *et al.*, 2017). Moreover, they can intensify the interaction between the contaminants and microorganisms by changing the surface microbial properties. Biosurfactants are known to have a dual amphipathic quality and they are produced by microorganisms such as bacteria, fungi and yeast (Sarubbo *et al.*, 2015; Olasanmi and Thring, 2018). Furthermore, they can also be produced by a diversity of animals and plants. Examples of microorganisms able to produce biosurfactants are *Saccharomyces lipolytica, Pseudomonas aeruginosa* and *Candida lipolitica* (Sáenz-Marta *et al.*, 2015; Maikudi Usman *et al.*, 2016). Amin (2018) reports that environmental biotechnology can be used in pollution prevention as a method of more efficiently cleaning wastes than most current methods. Furthermore, the author asserts that various types of bacteria flourishes when exposed to waste products. Therefore, environmental engineers can use microorganisms for bioremediation in different ways.

In simple terms, the process of environmental biotechnology in waste management is when nutrients are added to the landfill or any waste pile to stimulate bacterial activity or microorganisms already in the waste. In some instances, microorganisms can be added to the waste pile. In turn, the microorganism will react and digest the waste and turn it into harmless by products before assimilating into the natural environment. Simply put, bioremediation is "the naturally occurring process by which microorganisms either immobilize or transform environmental contaminants to innocuous end products" (Amin, 2018). Compared to toxic chemical and physical treatments, bioremediation is the lowest-cost technology that mineralises chemical contaminants permanently (Shao *et al.*, 2017). In other bioremediation methods, municipal solid waste can be converted into biofuel that can be used to produce electric power.

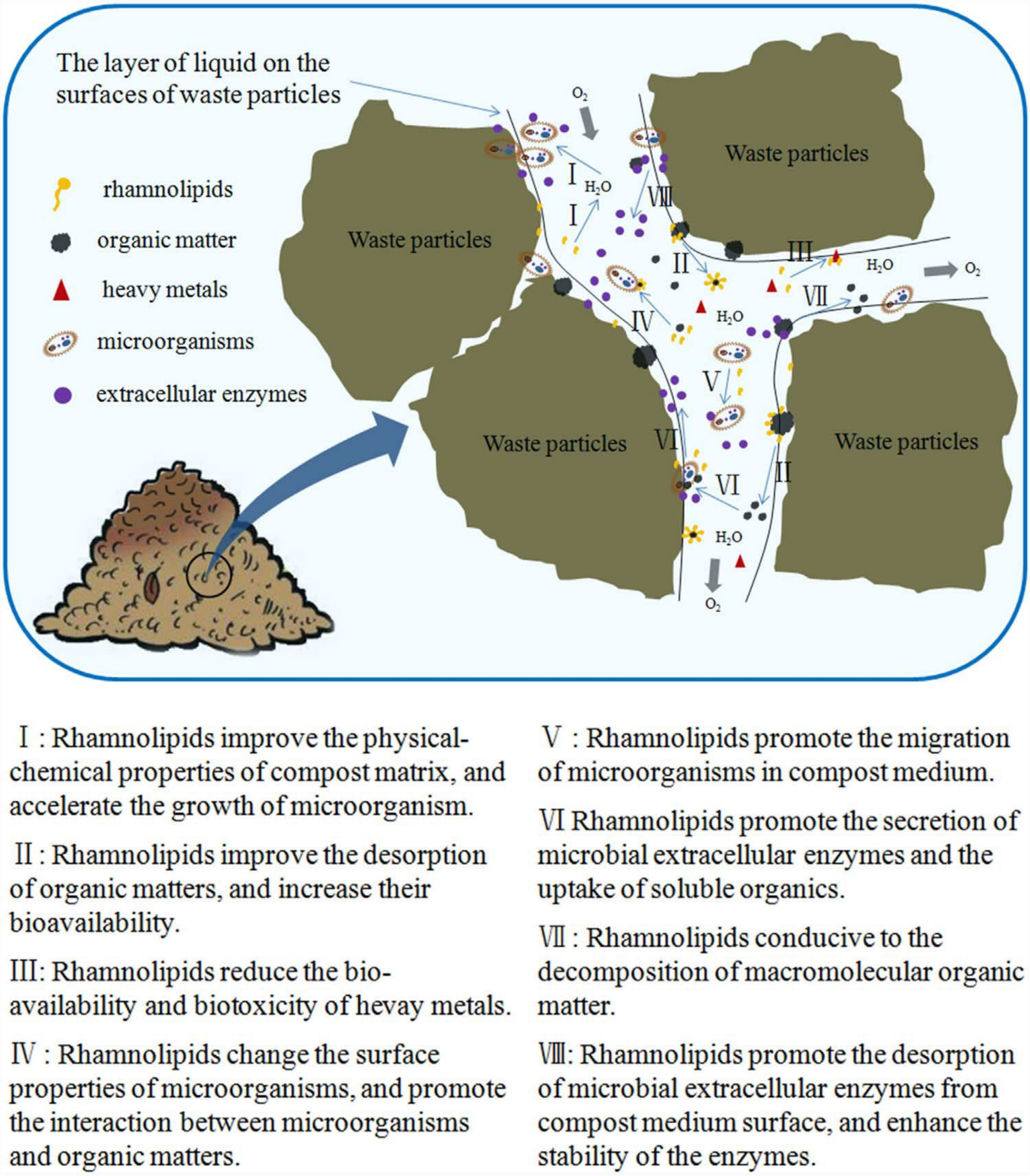
Bioremediation is one of the biological processes used to decrease pollutants in the environment. In effect, the process involves the transformation of organic pollutants (garden waste, food, etc.) by organisms. This, in turn, results in the production of less harmful substances. Microorganisms have natural degradation qualities; therefore, during bioremediation, the pollutants are turned into water and carbon dioxide and are thus integrated into various biogeochemical cycles (Maikudi Usman *et al.*, 2016; Olasanmi and Thring, 2018). Furthermore, biosurfactants are produced as secondary metabolites, more especially when growing on substrates such as hydrocarbons. Therefore, the use of biosurfactants produced by microorganisms has been found the most effective in the remediation of contaminated environments.

Interestingly, biosurfactants as solutions in the treatment of MSW do not have to be used after consumers have created the waste. Studies show that they can be used even along the waste production chain (Sáenz-Marta *et al.*, 2015). An example would be the application in the food and agriculture sector. This is also cost effective, because the waste from food and the use of agrochemicals can be used to produce low-cost biosurfactants (Sáenz-Marta *et al.*, 2015). Extensive research has been conducted on the study of microorganisms that produce biosurfactants. The structural diversity of biosurfactants make them efficient for vast industrial applications. Other researchers view biosurfactants as a tool in the bioremediation of polluted environments (Kaushal *et al.*, 2018). Therefore, there is a need to exploit the applicability of these biosurfactants optimally to advance municipal solid-waste operations and management.

According to Sarubbo *et al.* (2015), biological activity is not capable of remediating deep-lying heavy metals in soil. However, the researchers suggest that processes such as bioremediation can be used for long-term refurbishment, in combination with other rigorous methods. In the context of municipal solid waste, heavy-metal pollution caused by non-biodegradable materials can be remediated using microorganisms. This can happen when microbes alter the pH of the metal. Biosurfactants "facilitate the solubilisation, dispersal and desorption of contaminants in soil, thereby allowing the reuse of land". Even though the researchers report that biosurfactants can be applied to a small portion of contaminated soil after excavating trenches and applying the biosurfactant, the same principle can be hypothesised in landfill sites. Trenches can be dug to allow biosurfactants to be applied in larger quantities to reduce the impact of heavy-metal contamination (Pacwa-Płociniczak *et al.*, 2011; Sáenz-Marta *et al.*, 2015).

Rhamnolipid biosurfactants are the most cited in the bioremediation of heavy metals (Shao *et al.*, 2017). They are produced by the bacterial species *Pseudimonas aeruginosa* (Salmani Abyaneh and Fazaelipoor, 2016). In a study, the rhamnolipid foam was tested to be 73% efficient in the removal of cadmium and 68.1% effective in the removal of nickel (Sarubbo *et al.*, 2015). In this experiment, the results showed that the chemical composition of the soil influences the rate of metal removal (Sarubbo *et al.*, 2015; Das *et al.*, 2017). In another study to determine the removal of crude oil contamination in the soil, rhamnolipid biosurfactant was found to be 46% more effective than natural surfactant saponin (27%) (Liu *et al.*, 2017).

Rhamnolipids have been found to be effective in the formation of waste compost, as shown in Figure 6.9. The traditional composting time is long; however, with the addition of biosurfactants such as rhamnolipids, the time can be shortened with quality compost outputs. This mechanism is achieved by the rhamnolipid's capability to improve the porosity, pH, humidity and temperature. All these factors are conducive to the composition process. Basically, these factors promote the rapid growth of microorganisms. Rhamnolipids have beneficial properties in the creation of compost. However, the cost of production has hindered the practical application. Therefore, it is important to find alternative ways of producing rhamnolipids without adverse financially implications. Researchers (Shao *et al.*, 2017) have cautioned the use of this biosurfactant without rigorous toxicological studies to ascertain the possible dangers.



Ⅰ: Rhamnolipids improve the physical-chemical properties of compost matrix, and accelerate the growth of microorganism.

Ⅱ: Rhamnolipids improve the desorption of organic matters, and increase their bioavailability.

Ⅲ: Rhamnolipids reduce the bio-availability and biotoxicity of hevay metals.

Ⅳ: Rhamnolipids change the surface properties of microorganisms, and promote the interaction between microorganisms and organic matters.

Ⅴ: Rhamnolipids promote the migration of microorganisms in compost medium.

Ⅵ Rhamnolipids promote the secretion of microbial extracellular enzymes and the uptake of soluble organics.

Ⅶ: Rhamnolipids conducive to the decomposition of macromolecular organic matter.

Ⅷ: Rhamnolipids promote the desorption of microbial extracellular enzymes from compost medium surface, and enhance the stability of the enzymes.

Figure 6.9: Effects of rhamnolipids in composting (Adapted from Shao *et al*., 2017).

6.10. Leachate generation from solid waste and bioremediation

Leachate is a liquid by-product of the reaction of organic or inorganic matter after it has been exposed to water. According to Negi, Mor and Ravindra (2020), this formation occurs through chemical reactions, physical contact and the process of fermentation. Essentially, leachate is formed when there is rainfall on the shallow layers of waste piles. Then the water permeates the waste and is mixed with organic, inorganic, heavy metals and xenobiotic material

(Zurbrügg *et al.*, 2012; Ncube, Ncube and Voyi, 2017; Oelofse *et al.*, 2018). This is often problematic due to the potential of leachate flowing into municipal drainage systems through runoff water (Leton and Omotosho, 2004; Lindgreen and Lindgreen, 2004).

Leachate formation from dumpsites is noted as one of the major causes of pollution of groundwater in developed areas (Aboyeji and Eigbokhan, 2016; Enitan *et al.*, 2018). Moreover, natural water sources can be polluted by untreated waste effluents that are discharged into the environment (Leton and Omotosho, 2004). Landfills further exacerbate the leaching of toxic substances and thus become a risk factor (Vallero, 2019) due to chemical processes that occur predominantly in humid environments (Negi *et al.*, 2020).

In Nigeria it was reported that wastes are deposited in non-approved landfill sites where organic and inorganic compounds infiltrate into the groundwater (Aboyeji and Eigbokhan, 2016). As a result, this causes adverse environmental and health effects of varying levels due to chemical properties of the effluent. The following elements and compounds are usual constituents of leachate: sodium, potassium, sulphates (Leton and Omotosho, 2004; Parrot *et al.*, 2009), lead (Saleem *et al.*, 2018), copper, ammonium (Saleem *et al.*, 2018), magnesium, zinc, iron, manganese (Costa *et al.*, 2019), etc. This is by no means an exhaustive list; however, it shows the likelihood of chemical exposure of which its severity depends on toxicity and concentration of the leachate. As denoted in Figure 6.10a and 6.10b, the relationship between risk factor exposure and cancer risks from leachate contaminated water increases the risk of cancer. Toxic chemical exposure can lead to the development of cancerous cells. For this reason, toxicological studies often advocate the use of substances that are less harmless and environmentally friendly. It is therefore important to introduce biomolecules in the treatment of leachate because of the benefits to the environment and economic viability. Historically, leachate treatment has been proven to be expensive, therefore affordable biological strategies have been explored in the bioremediation of polluted environments as a way of supporting the global agenda on sustainable development.

The waste type globally generated the most is food waste. Therefore, daily food consumption results in increased waste generation. Therefore, the waste released into the environment may contain harmful pollutants such as heavy metals accumulated from the water and soil used to grow the food. Bioremediation methods have been used to alleviate the impact of these pollutants on the food and waste (Govarthanan *et al.*, 2016). In this context, yeasts, bacteria, cynobacteria, algae and plants have been used to absorb heavy metals (Massoud *et al.*, 2019). As noted by the mentioned researchers, *Saccharomyces cerevisiae,* also known as bakers' yeast, is used in the food industry and is known to be effective in metal biosorption. Various researchers have written extensively about heavy metals found in waste leachate (Leton and Omotosho, 2004; Zurbrügg *et al.*, 2012; Abd El-Salam and Abu-Zuid, 2015; El-Gohary and Kamel, 2016; Ncube *et al.*, 2017; Negi *et al.*, 2020).Therefore, there is a window of opportunity for further exploration of its application in municipal landfill sites that have been reported to have large quantities of heavy metals caused by waste.

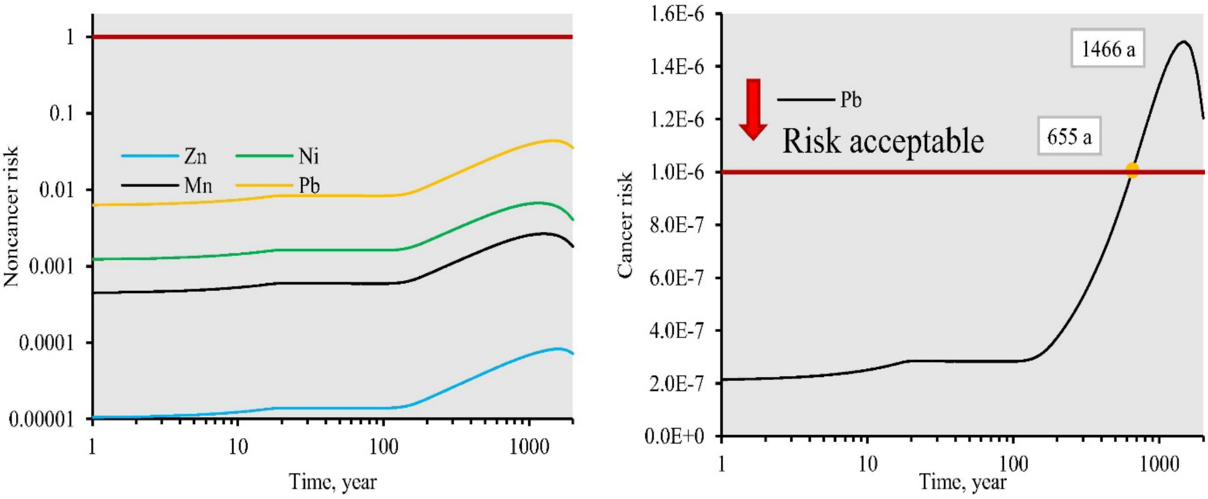


Figure 6.10a & b: Carcinogenic and noncarcinogenic effects of heavy metals (Adapted from Xu *et al.*, 2018).

The leachate properties and concentration can be analysed to assess the age of the landfill and its impact on the environment. The heavy concentration of heavy metals and severe contamination of organics in the environment are indications of the characteristics of waste disposed and the effectiveness of leachate membranes (Abd El-Salam and Abu-Zuid, 2015). Costa *et al.* (2019) report that the volume and quantity of leachate are dependent on a number of factors such as the amount of rain, the rate of evaporation, rate of absorption into the soil, waste density after compaction and surface water runoff. Furthermore, these factors could be managed using various leachate management techniques such as cover layers, waterproofing and linings.

Treatment options for leachate vary according to resources and financial stability of municipalities. Leachate can be treated using biological processes such as aerobic and anaerobic lagoons, as demonstrated in Figure 6.11 (Costa *et al.*, 2019). El-Gohary and Kamel

(2016) recommend that a certain percentage of the leachate effluent be diluted with sewage before biological treatment to facilitate microbial action. Further studies have reviewed other treatment options such as physical-chemical processes and membrane filtration (Costa *et al.*, 2019). All these technologies are viable options local authorities should explore and possibly implement.

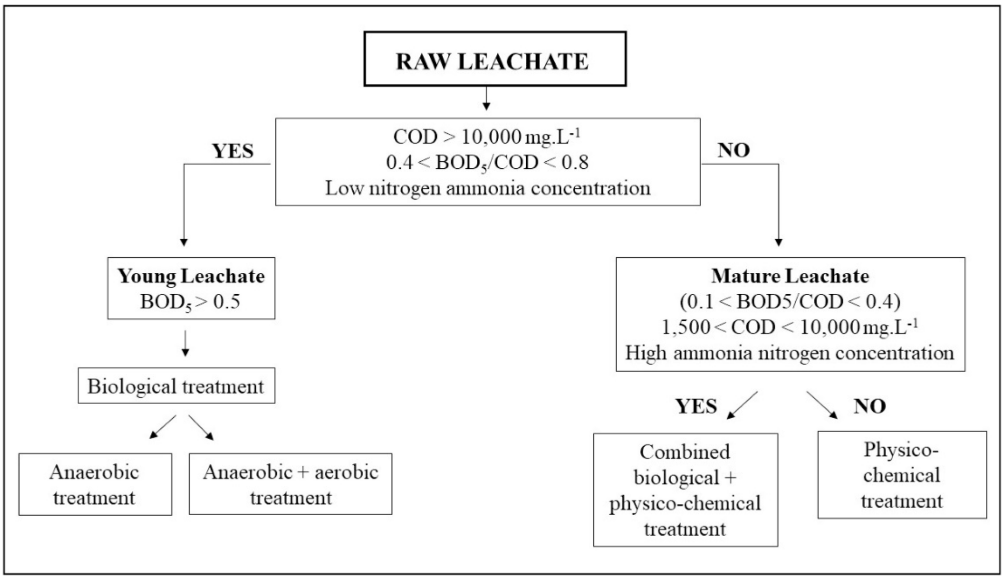


Figure 6.11: Raw leachate treatment options (Adapted from Costa *et al.,* 2019).

Organic contaminants resulting from MSW are problematic due to their hydrophobic properties, which make then difficult for local authorities to remediate when the need arises (Sáenz-Marta *et al.*, 2015). Amongst the soil and water remediation technologies there are surfactants which come in different forms of production. They can be produced through chemical manipulation or be biotechnologically based, thus called biosurfactants (Saleem *et al.*, 2018). Broadly speaking, these are naturally produced compounds with surfactant qualities (Sharma and Melkania, 2017). In the light of their application in remediating sites contaminated by municipal solid waste, they are highly regarded due to their low toxicity and effectiveness even in extreme temperatures and thus preferable compared to chemical-based surfactants. Moreover, they are known to be biocompatible and practical to apply. Therefore, bioremediation in the context of MSW facilitates the rapid biodegradation process in the contaminated environment by making available factors such as oxygen, nutrients, relevant microorganisms and conducive conditions such as pH and humidity content (Parrot *et al.*, 2009; Abd El-Salam and Abu-Zuid, 2015).

The use of technologies such as biosurfactants, is addressed by Vallero (2019), where he asserts that in waste governance, a wide range of technologies should be used as an effective approach to treat waste. Furthermore, he acknowledges that various stakeholders will need to be consulted through different communication platforms before the inception and commencement of any technological application.

6.11. Feasibility of technologies used in MSWM

Scientists are having an ongoing dialogue about the use of landfills as the ultimate method of final municipal solid-waste disposal. The disadvantages of this method have been extensively documented; however, the financial benefits thereof cannot be ignored, compared to the expensive, often impractical alternatives. These, however, bring opportunities to developing nations to come with other innovative technological solutions and policies tailor-made to their context (Aleluia and Ferrão, 2016; Leal Filho *et al.*, 2016; Enitan *et al.*, 2018). A study was conducted in the United Kingdom (UK) to assess the life-cycle environmental impacts of energy recovery from municipal solid waste. Two waste-to-energy options were explored, namely incineration and the bio-gas recovered from landfill. It was discovered that incineration has lower environmental impacts than landfilling across all the impact categories considered (Jeswani and Azapagic, 2016). The only downside was the human toxicity test where the incineration option showed higher potential toxic effects. Overall, landfilling had higher environmental impacts, although the incineration option had higher global warming contributions. Other countries are sceptical to use the incineration method due to its expensive energy fees and maintenance (Weng and Fujiwara, 2011). However, the use of the bioremediation has proven to the most economical method of treating polluted environments, compared to physical methods (Shao *et al.*, 2017).

Developed nations are in a quest to upgrade their facilities and landfilling equipment, while the developing countries are still attempting to be on par with best practices. The difference between the two extremes is the financial strength, knowledge about waste treatment options, limited facility resources, insufficient policies, regulations and experience (Sáenz-Marta *et al.*, 2015; Costa *et al.*, 2019). The inception of new technology in developing nations has disadvantages where the equipment may not be appropriate for certain conditions, thus resulting in breakdowns and improper practices. Furthermore, the adaption of the equipment to the conditions might be resource intensive.

Public utilities are governed by certain principles that ensure the efficiency of service delivery in local municipalities. It is thus recommended that they use a combination of initiatives to improve service standards. The use of technological innovations, internal and external auditing systems and improved procurement policies are known to escalate the efficiency level of public service utilities through due diligence and applying best practices (Guerrini *et al.*, 2017).

6.11.1. Biosurfactant application feasibility

Azubuike, Chikere and Okpokwasili (2016) report on the different types of bioremediation techniques. These researchers discuss the implications of various techniques regarding cost and practicality. Two technique methods are apparent in their discussion; *ex-situ* and *in-situ* bioremediation. *Ex-situ* techniques involve removing and excavating pollutants from affected sites and transporting them to a more controlled environment where they will be treated. Typical examples of the technique are the biopile-mediated method, windrows and the bioreactor method. The disadvantage of these techniques includes the cost of transportation and possible secondary contamination in the case of pollutant spills. Within the context of municipal solid waste, it will be difficult to transport all the waste generated to approved sites. Transportation to landfill sites and incineration plants is already costly. Therefore, this technology may not always be the best, especially in low-income countries. *In-situ* bioremediation techniques involve treating the polluted environments at the site of pollution. Examples of such methods include bioventing, bioslurping, biosparging, intrinsic bioremediation and phytoremediation (Azubuike *et al.*, 2016). In municipal waste management, this technique will work the best in countries using landfills where biosurfactants can be applied in a controlled environment.

6.12 Environmental management and sustainable development

Environmental management is one of the critical global debates regarding the issues of sustainability that are raised on international podiums. During United Nations meetings, issues of priority on the global agenda are debated by both developed and developing countries. In the context of building a sustainable earth society, several needs must be met. A pollution-free earth is a wide-reaching topic; however, not all nations have the same understanding in terms of what is required to fulfil the pledge of a sustainable society (Beyerlin and Marauhn, 2011). Multiple authors have reported on the requirements for a sustainable earth society. A few points to note are: establishing a stable world population; improving energy production whilst minimising environmental impacts; waste and pollution control; and equitable global economy (Mazzi *et al.*, 2016).

The effective enforcement and implementation of legislation are processes that cannot be taken for granted. These processes can have detrimental effects, to a point where the processes face rejection by the residents they are supposed to protect. It is proven that most countries can be meticulous in planning; however, the execution is usually their downfall. This leads to principles of governance in waste management that should be deliberated holistically. Various authors have reported on notable agenda points in high offices in order to categorise processes of consideration when running effective MSWM programmes (Leal Filho *et al.*, 2016; Vallero, 2019). The central themes arising from the reports can be summed up as transparency, accountability legal processes, legitimacy and increased capacity for governmental institutions.

The inception of standards such as the Iso 14001, which is a voluntary leading tool in Environmental Management systems (EMSs), has benefited a lot of organisations globally regarding the protection of the environment and sustainability (To and Lee, 2014). This standard in particular has informed policies and other management tools in support of environmental sustainability (Mazzi *et al.*, 2016; Xu *et al.*, 2018) and waste reduction. It has been revised several times since its inception in the 1990s, with the aim to improve the practicability and ambiguous terms. The aim of the standard is to support organisations to control environmental aspects and impacts (Franchetti, 2011); thus leading to efficient operations and accountability by the implicated organisations. Therefore, this standard should be one of the tools used to monitor the impact of municipal solid waste on the environment, and perhaps be used to measure the efficiency of MSW operations.

Environmental management systems are regarded as essential tools that guide and support policies of governments and interested organisations. Receiving certification from such international codes demonstrates the intensions of the organisation in terms of competencies and international best practices (Xu *et al.*, 2018). This suggests that all entities with operations that may cause adverse environmental impacts should consider adopting such tools to protect not only the business, but the ecosystem at large. To date, the drawbacks of adopting environmental management systems have been the financial implications relating to the implementation of the EMS (Franchetti, 2011). In the sustainable development agenda, using cleaner technologies has to be a priority, thus leading to most organisations' reluctance to adopt the systems. All these imply that organisations, including municipalities, might be reluctant to use the standards due to cost implications and the fear of the likelihood of non-conformance to the standard.

6.13. Environmental sustainability using biosurfactants

Considering the call for global stakeholders to produce sustainable products, the technology using biosurfactants has been increasing more, especially in developed nations. The vast application of biosurfactants assists in environmental sustainability in various ways. It is anticipated that biosurfactants will play a role in renewable by-products as substrates (Olasanmi and Thring, 2018). Moreover, they will play a pivotal role in some components of the waste management hierarchy, i.e. waste reduction and the re-purposing of treated municipal waste. The increase in environmental pollution requires innovative ways of protecting the environment. Generally, industries find it difficult to balance sustainable, eco-friendly technologies and the efficiency of operations. Even though legislation requires minimal environmental pollution and effective, best practical remediation strategies, the total cost of the technology is often problematic to polluters. Santos *et al.* (2016) report that the study of biosurfactants began in the 1960s and technology has since improved from that era. In recent publications, research on the applications of biosurfactants has started over two decades ago and the field has been making significant strides, compared to the latter years (Olasanmi and Thring, 2018).

Historically, the cost of treating polluted environments, especially anthropogenic activities such as waste generation, has been costly. Therefore, the inception of biosurfactant as an alternative to remediate the contaminated environment has been a viable option. However, industries need to find cost-effective methods of the mass production of biosurfactants. The effect of green-house gases because of municipal solid waste has been recorded in most landfill sites and these has prompted the need for new methods of waste reduction and control. As a result, biosurfactants are used to reduce the concentration of some of the gases emitted into the atmosphere. Environmental sustainability in waste-disposal sites is imperative, considering that most of the waste disposed is of synthetic nature. Consequently, it is vital for authorities to opt for biodegradable technologies instead of synthetic technologies when remediating the sites. This notion is supported by Olasanmi and Thring (2018), who assert that a product is considered to be sustainable when its performance is better than that of its closest competitor. Some studies have found the large-scale production of biosurfactants to be costly in relation to the use of synthetic surfactants (Sarubbo *et al.*, 2015). Biosurfactants have been reported to be 20–30% more expensive, compared to synthetic surfactants (Olasanmi and Thring, 2018). Essentially, more research needs to be conducted to ascertain the feasibility of large-scale biosurfactant production.

In an endeavour to reduce waste generation, substrates from food waste can be used to produce biosurfactants. An example would be the use of potato peels to facilitate the production of lipopeptide biosurfactant using *Bacillus subtilis*. In other methods, renewable, low-cost, agro-industrial waste such as vegetable oils have been used to produce biosurfactants. Generally, the use of cheap substrate can lower the cost of production of these biomolecules. However, authors caution that a suitable substrate needs to be selected to meet the requirement for optimal biosurfactant production, microbial action and growth (Sarubbo *et al.*, 2015). The substrate must have nutrients such as lipids and carbohydrates. In summary, the use of substrates is economically viable in terms of reducing the cost of waste management by industries. In waste management, biosurfactants do not need to be pure like in pharmaceutical applications. This alone significantly lowers the cost of production. Thus, biosurfactants remain the best alternative that reduces the use of toxic solvents and various organic solvents in environmental cleansing.

6.14. Municipal solid-waste management infrastructure and financing

Advocates of environmental sustainability have viewed the used of landfill as ‘money in the drain’ due to the amount of waste disposed daily. There is currently little effort to remunerate citizens who recycle their waste. Furthermore, the street pickers’ efforts are enormous; yet little impact is achieved in reducing the burden of waste generated in municipalities (Al-Jarallah and Aleisa, 2014). There has been global calls to reduce waste generation due to the emergence of factors such as global warming and sustainable development. However, public awareness on a global scale is a daunting task, especially when each nation has its own pressing matters (Manga *et al.*, 2011).

The usage of waste transfer stations by nongovernmental organisations and community-based organisations requires technical, institutional and funding support (Parrot *et al.*, 2009). Zhang *et al.* (2014) propose an interactive model that assists with planning of transportation and inventory for organisation throughout the waste management process (collection, delivery and disposal). Fundamentally, this is a supply-chain system that will control planning for real-time and long-term municipal solid waste regarding supplies, inventories, production levels and operational devices, consequently, decreasing the cost implications relating to waste management. This supply-chain model can be used is a variety of scenarios; however, its viability in developing nations is yet to be tested (Zhang *et al.*, 2014).

Comprehensive strategic plans need to be developed to deal with the pressures of MSW management, especially from the informal sector, which is an emerging market on its own and a major contributor. Governments have recognised the relationship between urban planning and waste management. Accordingly, resources are now being made available to secure the funding necessary for urban development in heavily indebted countries (Parrot *et al.*, 2009).

Inefficient MSWM could be attributed to an array of factors such as access to proper roads and the development of informal settlements. This collection of challenges further puts a strain on the already scare resources like garbage bins in relation to the population numbers and how these bins are distributed in residential areas (Guerrini *et al.*, 2017). A study in Verona, Italy addressed the integration of collection services in small municipalities and it was concluded that the integration of these services was not beneficial. The main challenge was integrating the already stretched financial resources and transboundary logistics. Perhaps a system where such issues are considered in the planning phase could assist in the implementation phase.

Municipal solid-waste management services can be hampered by a wide variety of factors such climate-related environmental factors. In rainy seasons, unpaved roads are generally inaccessible in developing countries with poor infrastructure such as municipal drainage systems and proper roads (Kasinja and Tilley, 2018). This has a direct effect on waste collection due to occupational hazards by the waste collectors, design of the vehicles, etc. Ideally, the rate of waste generation must be equivalent to the rate of waste collection, as supported by Parrot *et al.* (2009). In their study, they discovered that the mean growth rate for municipal waste generation and collection was 10.4% and 9.5% between the year 2002 and 2005, respectively. The rate of waste generation was higher than that of waste collection. Consequently, the more waste was left unattended, the more waste was disposed of in an unapproved manner in low- and middle-income countries (Parrot *et al.*, 2009). The effects of such scenarios are evident in open spaces, rivers, forests and areas such as school and church sidewalks where there is no individual accountability and a sense of belonging. This is a phenomenon best explained in health sciences as health-promoting behavioural patterns.

The health-behavioural-pattern concept is explained better by the health-belief model, which is a social psychological health-behaviour change model established to elucidate and forecast health-related behaviours (Ma and Hipel, 2016). This model suggests that what people believe about health consequences and the benefit thereof can trigger a change in behaviour, or at least allow them to participate in health-promoting behaviours. There are other underlying factors that exacerbate behavioural patterns that are not conducive to the overall concept of implementing an municipal solid-waste management system. Such patterns are influenced by lack of public knowledge, otherwise known as the information barrier (Ma and Hipel, 2016).

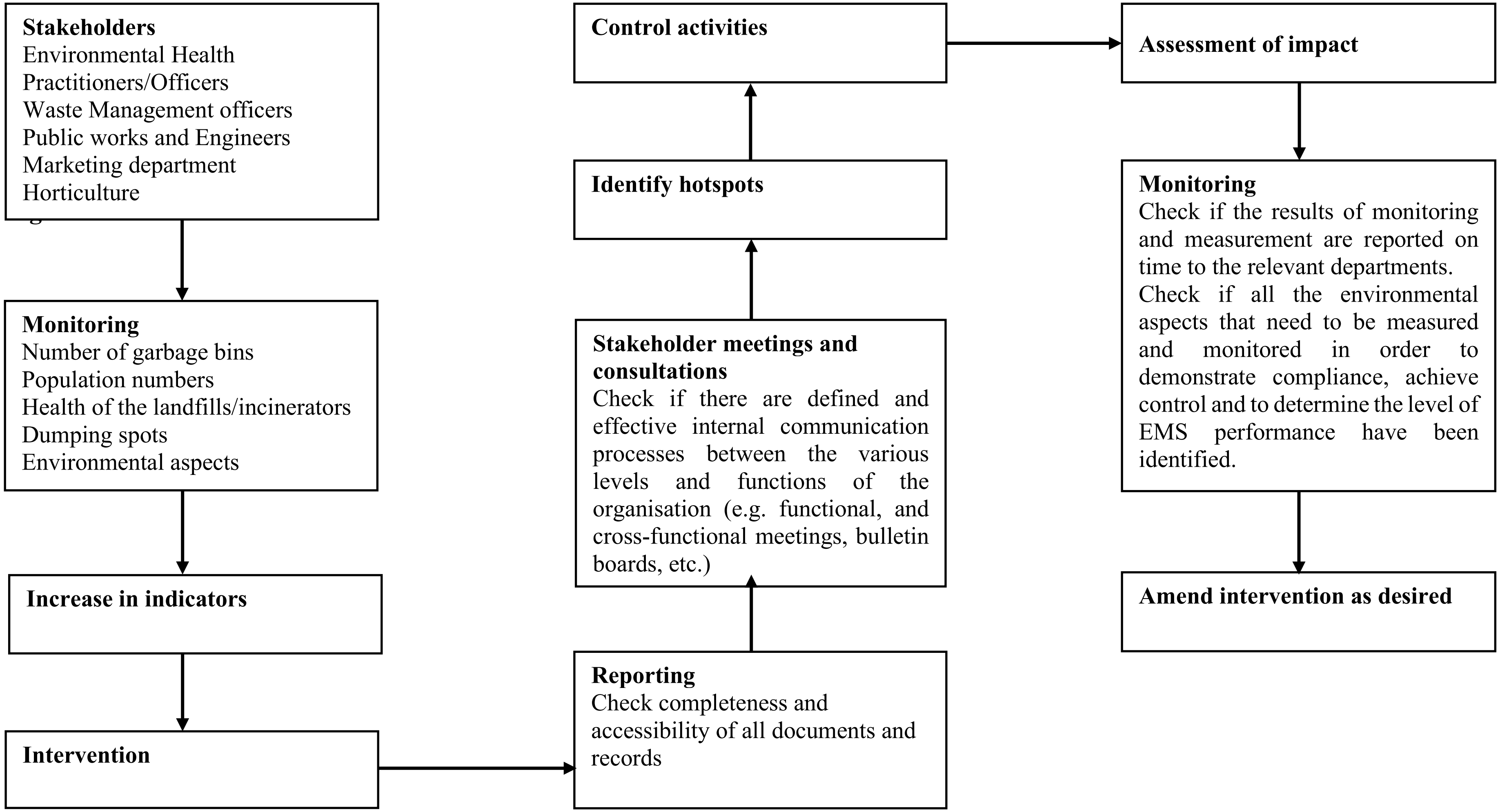
6.15 Municipal solid-waste management financial and institutional challenges

To reduce the burden of waste disposal, some municipalities globally depend on tax rebates from the citizens to fund the MSW management activities. Notably in South Africa, the government has enforced a law where the polluter must pay. This is to ensure that all citizens take responsibility for their activities by causing less pollution and ecological degradation (South Africa, 2004). This implies that whoever has the capacity to cause harm or pollute the environment is liable to pay or remediate (Ma and Hipel, 2016). Essentially, this payment can be in the form of municipal rates for solid-waste collection or even a fine payable for non-conformance to municipal by-laws (Dlamini, Rampedi and Ifegbesan, 2017; Guerrini *et al.*, 2017). However, there are challenges to such laws in developing countries where there is an informal sector filled with indigents. Instituting such tax liabilities to residents who have no proper shelter and are already on social welfare is a challenge on its own (Dlamini *et al.*, 2017).

Exorbitant management costs are a call for concern in most developing countries. Waste collection, transfer and transport constitutes a significant portion of the overall cost of managing waste. Different sources of information have estimated figures linked to MSW management. Researchers (Leal Filho *et al.*, 2016) have estimated that close to 80–90% of the total budget goes to waste collection, transfer and transportation. There are instances reported where users do not want to pay service fees or strictly cannot afford them. In addition, insufficient budget could be a stumbling block to MSWM provision. Funds could be mismanaged, thus creating a gap in service delivery. Municipalities falling under the European Union (EU) have pledged to abide by key policies to achieve the best possible quality standards such as financing municipal waste within reasonable means.

Another obstacle to efficient MSWM is the clarity of roles and efficiency in government departments. Generally, municipalities are set out into sub-departments with regard to waste management, namely enforcement, education, collection, cleansing, etc. (Leal Filho *et al.*, 2016). This strategy needs further testing and validation; however, it is one of the viable comprehensive models that can be adopted. Enforcement and education are usually conducted by Environmental Health Practitioners/Officers, as defined by the World Health Organization (WHO), or with the assistance of parallel colleagues such as waste-management officers, as demonstrated in Figure 6.12. Ideally, a waste-management team should at least encompass the following professionals in addition to the above-mentioned disciplines: civil and mechanical engineers, accountants, marketing and multimedia, machine operators, manual labourers or technicians, etc. Lack of capacity in integrated waste management is a long-standing concern that has led to the participation of different stakeholders such as the private sector, which bring specialised technological services, cost efficiency, skilled personnel and capital resources to municipalities. This has led to more stakeholder collaboration from community-based organisations in the form of environmental cadres (Dhokhikah, Trihadiningrum and Sunaryo, 2015; Leal Filho *et al.*, 2016; Ma and Hipel, 2016; Ablo and Yekple, 2018).

Ma and Hipel (2016) raised critical issues pertaining to financing MSW partnerships; firstly, the tendering process and lack of transparency in awarding contracts and leases. By implication, the most qualified may not win the contract. It has been widely reported that certain organisations cannot meet their obligations due to the mismanagement of funds after being awarded a lucrative contract. As a result, this affects service delivery and future plans. Secondly, there might be a lack of practical implementation plans and monitoring standards. Lastly, there has been reports of dysfunctional management issues regarding late payments of contracts and subsidies not processed on time, thus hindering operational plans.



Stakeholders
Environmental Health Practitioners/Officers
Waste Management officers
Public works and Engineers
Marketing department
Horticulture

Monitoring
Number of garbage bins
Population numbers
Health of the landfills/incinerators
Dumping spots
Environmental aspects

Increase in indicators

Intervention

Reporting
Check completeness and accessibility of all documents and records

Stakeholder meetings and consultations
Check if there are defined and effective internal communication processes between the various levels and functions of the organisation (e.g. functional, and cross-functional meetings, bulletin boards, etc.)

Identify hotspots

Control activities

Assessment of impact

Monitoring
Check if the results of monitoring and measurement are reported on time to the relevant departments.
Check if all the environmental aspects that need to be measured and monitored in order to demonstrate compliance, achieve control and to determine the level of EMS performance have been identified.

Amend intervention as desired

Figure 6.12: Schematic diagram demonstrating the conceptual model of possible interventions in managing MSW through stakeholder consultation, law enforcement and routine inspections.

6.16. Conclusion

Municipal solid waste has been one of the long-standing global debates in the past and recent years. The magnitude of the health and environmental impacts has been reported extensively across different platforms with the hope to change policies and influence behaviours worldwide. This has also presented opportunities for technologies in the bioremediation of polluted environments.

The ever-increasing generation of waste in municipalities is a call for concern, considering the lack of resources, especially in low-income countries that are still battling with obsolete technology in municipal solid-waste management. These has negative consequences, considering the population numbers and the type of waste disposed in landfills. There is sufficient evidence proving the detrimental impact of landfills on the health of nearby communities and workers exposed to the waste. Therefore, the introduction of biosurfactants in the bioremediation of municipal solid waste is an option worth exploring. Considering the benefits of biosurfactants, more studies need to be conducted to ascertain their applicability and mass production.

Ultimately, to ensure a sustainable environment, governments must formulate enabling policy frameworks tailored to their context. This assists in developing targeted interventions specific to a region or country’s needs. Moreover, it strengthens programmes already in place and supplements for the implementation of Environmental Management systems. Managing solid waste in municipalities comes with a wide range of challenges, from financing to outsourcing the required expertise and equipment. Therefore, it is the responsibility of municipalities to seek for the best available technologies that are environmentally sound and economically viable.

6.17 References

Abbasi, M. and El Hanandeh, A. (2016) ‘Forecasting municipal solid waste generation using artificial intelligence modelling approaches’, *Waste Management*, 56, pp. 13–22. doi: 10.1016/j.wasman.2016.05.018.

Abd El-Salam, M. M. and Abu-Zuid, G. I. (2015) ‘Impact of landfill leachate on the groundwater quality: A case study in Egypt', *Journal of Advanced Research*, 6(4), pp. 579–586. doi: 10.1016/j.jare.2014.02.003.

Ablo, A. D. and Yekple, E. E. (2018) 'Urban water stress and poor sanitation in Ghana: perception and experiences of residents in the Ashaiman Municipality', *GeoJournal*, 83(3), pp. 583–594. doi: 10.1007/s10708-017-9787-6.

Aboyeji, O. S. and Eigbokhan, S. F. (2016) 'Evaluations of groundwater contamination by leachates around Olusosun open dumpsite in Lagos metropolis, southwest Nigeria', *Journal of Environmental Management*, 183, pp. 333–341. doi: 10.1016/j.jenvman.2016.09.002.

Abubakar, I. R. (2017) 'Household Response to Inadequate Sewerage and Garbage Collection Services in Abuja, Nigeria', *Journal of Environmental and Public Health*, 2017. doi: 10.1155/2017/5314840.

Aleluia, J. and Ferrão, P. (2016) 'Characterization of urban waste management practices in developing Asian countries: A new analytical framework based on waste characteristics and urban dimension', *Waste Management*, 58, pp. 415–429. doi: 10.1016/j.wasman.2016.05.008.

Al-Jarallah, R. and Aleisa, E. (2014) 'A baseline study characterizing the municipal solid waste in the State of Kuwait', *Waste Management*, 34(5), pp. 952–960. doi: 10.1016/j.wasman.2014.02.015.

Amin, T. (2018) 'Application of Biotechnology in Food Plant Waste Utilization', *International Journal of Advances in Science Engineering and Technology*, 6(3), pp. 33–36.

Aparcana, S. (2017) 'Approaches to formalization of the informal waste sector into municipal solid waste management systems in low- and middle-income countries: Review of barriers and success factors', *Waste Management*, 61, pp. 593–607. doi: 10.1016/j.wasman.2016.12.028.

Azubuike, C. C., Chikere, C. B. and Okpokwasili, G. C. (2016) 'Bioremediation techniques–classification based on site of application: principles, advantages, limitations and prospects', *World Journal of Microbiology and Biotechnology*, 32(11), pp. 1–18. doi:

10.1007/s11274-016-2137-x.

Beyerlin, U. and Marauhn, T. (2011) ‘International Environmental Law’, *International Environmental Law*, 41(Summer), pp. 1–13. doi: 10.5771/9783845265582.

Coban, A., Ertis, I. F. and Cavdaroglu, N. A. (2018) ‘Municipal solid waste management via multi-criteria decision making methods: A case study in Istanbul, Turkey’, *Journal of Cleaner Production*, 180, pp. 159–167. doi: 10.1016/j.jclepro.2018.01.130.

Costa, A. M., Alfaia, R. G. de S. M. and Campos, J. C. (2019) ‘Landfill leachate treatment in Brazil – An overview’, *Journal of Environmental Management*, 232, pp. 110–116. doi: 10.1016/j.jenvman.2018.11.006.

Das, A. J. *et al.* (2017) ‘Bacterial biosurfactants can be an ecofriendly and advanced technology for remediation of heavy metals and co-contaminated soil’, *International Journal of Environmental Science and Technology*, 14(6), pp. 1343–1354. doi: 10.1007/s13762-016-1183-0.

Dhokhikah, Y., Trihadiningrum, Y. and Sunaryo, S. (2015) ‘Community participation in household solid waste reduction in Surabaya, Indonesia’, *Resources, Conservation and Recycling*, 102, pp. 153–162. doi: 10.1016/j.resconrec.2015.06.013.

Dlamini, B. R., Rampedi, I. T. and Ifegbesan, A. P. (2017) ‘Community resident’s opinions and perceptions on the effectiveness of waste management and recycling potential in the Umkhanyakude and Zululand district municipalities in the KwaZulu-Natal Province of South Africa’, *Sustainability (Switzerland)*, 9(10), pp. 1–20. doi: 10.3390/su9101835.

El-Gohary, F. A. and Kamel, G. (2016) ‘Characterization and biological treatment of pre-treated landfill leachate’, *Ecological Engineering*, 94, pp. 268–274. doi: 10.1016/j.ecoleng.2016.05.074.

Enitan, I. T. *et al.* (2018) ‘Human Health Risk Assessment of Trace Metals in Surface Water Due to Leachate from the Municipal Dumpsite by Pollution Index: A Case Study from Ndawuse River, Abuja, Nigeria’, *Open Chemistry*, 16(1), pp. 214–227. doi: 10.1515/chem-2018-0008.

Franchetti, M. (2011) ‘ISO 14001 and solid waste generation rates in US manufacturing organizations: An analysis of relationship’, *Journal of Cleaner Production*, 19(9–10), pp. 1104–1109. doi: 10.1016/j.jclepro.2011.01.004.

Govarthanan, M. *et al.* (2016) ‘Bioremediation of heavy metals using an endophytic bacterium Paenibacillus sp. RM isolated from the roots of Tridax procumbens’, *3 Biotech*, 6(2), pp. 1–7. doi: 10.1007/s13205-016-0560-1.

Gu, B. *et al.* (2015) ‘Characterization, quantification and management of household solid waste: A case study in China’, *Resources, Conservation and Recycling*, 98, pp. 67–75. doi: 10.1016/j.resconrec.2015.03.001.

Guerrini, A. *et al.* (2017) ‘Assessing efficiency drivers in municipal solid waste collection services through a non-parametric method’, *Journal of Cleaner Production*, 147, pp. 431–441. doi: 10.1016/j.jclepro.2017.01.079.

Hettiarachchi, H., Meegoda, J. N. and Ryu, S. (2018) ‘Organic Waste Buyback as a Viable Method to Enhance Sustainable Municipal Solid Waste Management in Developing Countries’, *International journal of environmental research and public health*, 15(11), pp. 1–16. doi: 10.3390/ijerph15112483.

Jayakrishnan, T., Jeeja, M. and Bhaskar, R. (2013) ‘Occupational health problems of municipal solid waste management workers in India’, *International Journal of Environmental Health Engineering*, 2(1), p. 42. doi: 10.4103/2277-9183.122430.

Jeswani, H. K. and Azapagic, A. (2016) ‘Assessing the environmental sustainability of energy recovery from municipal solid waste in the UK’, *Waste Management*, 50, pp. 346–363. doi: 10.1016/j.wasman.2016.02.010.

Jonjić, D. and Vitale, K. (2014) ‘Issues around household pharmaceutical waste disposal through community pharmacies in Croatia’, *International Journal of Clinical Pharmacy*, 36(3), pp. 556–563. doi: 10.1007/s11096-014-9936-7.

Kasinja, C. and Tilley, E. (2018) ‘Formalization of informal waste pickers’ cooperatives in Blantyre, Malawi: A feasibility assessment’, *Sustainability (Switzerland)*, 10(4), pp. 1–17. doi: 10.3390/su10041149.

Kaushal, J. *et al.* (2018) 'Catalase enzyme: Application in bioremediation and food industry', *Biocatalysis and Agricultural Biotechnology*, 16, pp. 192–199. doi: 10.1016/j.bcab.2018.07.035.

Kawai, K. and Tasaki, T. (2016) 'Revisiting estimates of municipal solid waste generation per capita and their reliability', *Journal of Material Cycles and Waste Management*, 18(1), pp. 1–13. doi: 10.1007/s10163-015-0355-1.

Leal Filho, W. *et al.* (2016) 'Benchmarking approaches and methods in the field of urban waste management', *Journal of Cleaner Production*, 112, pp. 4377–4386. doi: 10.1016/j.jclepro.2015.09.065.

Letcher, T. M. and Slack, R. (2019) *Chemicals in Waste: Household Hazardous Waste*. 2nd edn, *Waste*. 2nd ed. Elsevier Inc. doi: 10.1016/b978-0-12-815060-3.00017-7.

Leton, T. G. and Omotosho, O. (2004) 'Landfill operations in the Niger delta region of Nigeria', *Engineering Geology*, 73(1–2), pp. 171–177. doi: 10.1016/j.enggeo.2003.12.006.

Lindgreen, A. and Lindgreen, A. (2004) 'Corruption and unethical behavior: report on a set of Danish guidelines', *Journal of Business Ethics*, 51(1), pp. 31–39. doi: 10.1023/B.

Liu, Z. *et al.* (2017) 'Recent advances in the environmental applications of biosurfactant saponins: A review', *Journal of Environmental Chemical Engineering*, 5(6), pp. 6030–6038. doi: 10.1016/j.jece.2017.11.021.

Ma, J. and Hipel, K. W. (2016) 'Exploring social dimensions of municipal solid waste management around the globe – A systematic literature review', *Waste Management*, 56, pp. 3–12. doi: 10.1016/j.wasman.2016.06.041.

Maikudi Usman, M. *et al.* (2016) 'Application of biosurfactants in environmental biotechnology; remediation of oil and heavy metal', *AIMS Bioengineering*, 3(3), pp. 289–304. doi: 10.3934/bioeng.2016.3.289.

Manga, V. E. *et al.* (2011) 'Health care waste management in Cameroon: A case study from the Southwestern Region', *Resources, Conservation and Recycling*, 57, pp. 108–116. doi: 10.1016/j.resconrec.2011.10.002.

Marshall, R. E. and Farahbakhsh, K. (2013) ‘Systems approaches to integrated solid waste management in developing countries’, *Waste Management*, 33(4), pp. 988–1003. doi: 10.1016/j.wasman.2012.12.023.

Massoud, R. *et al.* (2019) ‘Bioremediation of heavy metals in food industry: Application of Saccharomyces cerevisiae’, *Electronic Journal of Biotechnology*, 37, pp. 56–60. doi: 10.1016/j.ejbt.2018.11.003.

Mazzi, A. *et al.* (2016) ‘What are the benefits and difficulties in adopting an environmental management system? The opinion of Italian organizations’, *Journal of Cleaner Production*, 139, pp. 873–885. doi: 10.1016/j.jclepro.2016.08.053.

Mohammed, A. *et al.* (2017) ‘solid waste management environmental impacts in Addis Ababa city’, *Journal of Environment and waste management*, 4(1), pp. 194–203.

National Department of Health (2004) ‘National Health Act, No. 61 of 2003’, *Government Gazette*, 463(61). Available at: https://www.up.ac.za/media/shared/12/ZP_Files/health-act.zp122778.pdf [5 November 2018].

Ncube, F., Ncube, E. J. and Voyi, K. (2017) ‘Bioaerosols, Noise, and Ultraviolet Radiation Exposures for Municipal Solid Waste Handlers’, *Journal of Environmental and Public Health*, 2017. doi: 10.1155/2017/3081638.

Negi, P., Mor, S. and Ravindra, K. (2020) ‘Impact of landfill leachate on the groundwater quality in three cities of North India and health risk assessment’, *Environment, Development and Sustainability*, 22(2), pp. 1455–1474. doi: 10.1007/s10668-018-0257-1.

Oelofse, S., Muswema, A. and Ramukhwatho, F. (2018) ‘Household food waste disposal in South Africa: A case study of Johannesburg and Ekurhuleni’, *South African Journal of Science*, 114(5–6), pp. 40–46. doi: 10.17159/sajs.2018/20170284.

Okuda, I. and Thomson, V. E. (2007) ‘Regionalization of municipal solid waste management in Japan: Balancing the proximity principle with economic efficiency’, *Environmental Management*, 40(1), pp. 12–19. doi: 10.1007/s00267-006-0194-x.

Olasanmi, I. O. and Thring, R. W. (2018) ‘The role of biosurfactants in the continued drive for environmental sustainability’, *Sustainability (Switzerland)*, 10(12), pp. 1–12. doi: 10.3390/su10124817.

Pacwa-Płociniczak, M. *et al.* (2011) ‘Environmental applications of biosurfactants: Recent advances’, *International Journal of Molecular Sciences*, 12(1), pp. 633–654. doi: 10.3390/ijms12010633.

Parrot, L., Sotamenou, J. and Dia, B. K. (2009) ‘Municipal solid waste management in Africa: Strategies and livelihoods in Yaoundé, Cameroon’, *Waste Management*, 29(2), pp. 986–995. doi: 10.1016/j.wasman.2008.05.005.

Pérez-López, G. *et al.* (2016) ‘Cost efficiency in municipal solid waste service delivery. Alternative management forms in relation to local population size’, *European Journal of Operational Research*, 255(2), pp. 583–592. doi: 10.1016/j.ejor.2016.05.034.

Sáenz-Marta, C. I. *et al.* (2015) ‘Biosurfactants as Useful Tools in Bioremediation’, in *Advances in Bioremediation of Wastewater and Polluted Soil*. doi: 10.5772/60751.

Saleem, M. *et al.* (2018) ‘Assessment of dynamic membrane filtration for biological treatment of old landfill leachate’, *Journal of Environmental Management*, 213, pp. 27–35. doi: 10.1016/j.jenvman.2018.02.057.

Salmani Abyaneh, A. and Fazaelipoor, M. H. (2016) ‘Evaluation of rhamnolipid (RL) as a biosurfactant for the removal of chromium from aqueous solutions by precipitate flotation’, *Journal of Environmental Management*, 165, pp. 184–187. doi: 10.1016/j.jenvman.2015.09.034.

Santos, D. K. F. *et al.* (2016) ‘Biosurfactants: Multifunctional biomolecules of the 21st century’, *International Journal of Molecular Sciences*, 17(3), pp. 1–31. doi: 10.3390/ijms17030401.

Sarubbo, L. A. *et al.* (2015) ‘Some aspects of heavy metals contamination remediation and role of biosurfactants’, *Chemistry and Ecology*, 31(8), pp. 707–723. doi: 10.1080/02757540.2015.1095293.

Seyring, N. *et al.* (2016) ‘Assessment of collection schemes for packaging and other recyclable waste in European Union-28 Member States and capital cities', *Waste Management and Research*, 34(9), pp. 947–956. doi: 10.1177/0734242X16650516.

Shao, B. *et al.* (2017) 'Effects of rhamnolipids on microorganism characteristics and applications in composting: A review', *Microbiological Research*, 200, pp. 33–44. doi: 10.1016/j.micres.2017.04.005.

Shar, N. *et al*. (2016) 'Biosurfactant: Types, Detection Methods, Importance and Applications', *Indian Journal of Microbiology Research*, 3(1), p. 5. doi: 10.5958/2394-5478.2016.00002.9.

Sharma, P. and Melkania, U. (2017) 'Biosurfactant-enhanced hydrogen production from organic fraction of municipal solid waste using co-culture of E. coli and Enterobacter aerogenes', *Bioresource Technology*, 243, pp. 566–572. doi: 10.1016/j.biortech.2017.06.182.

South Africa (2004) *NEMA: Waste Act 59 (2008)*, *Prevention*. South Africa: Government printer, South Africa. doi: 102GOU/B.

To, W. M. and Lee, P. K. C. (2014) 'Diffusion of ISO 14001 environmental management system: Global, regional and country-level analyses', *Journal of Cleaner Production*, 66, pp. 489–498. doi: 10.1016/j.jclepro.2013.11.076.

Vallero, D. A. (2019) *Waste Governance*. 2nd ed, *Waste*. 2nd ed. Elsevier Inc. doi: 10.1016/b978-0-12-815060-3.00033-5.

Vallero, D. A. and Shulman, V. (2019) 'Introduction to Waste Management', *Waste*, pp. 3–14. doi: 10.1016/b978-0-12-815060-3.00001-3.

Varjani, S. J. and Upasani, V. N. (2017) 'Critical review on biosurfactant analysis, purification and characterization using rhamnolipid as a model biosurfactant', *Bioresource Technology*, 232, pp. 389–397. doi: 10.1016/j.biortech.2017.02.047.

Weng, Y. C. and Fujiwara, T. (2011) 'Examining the effectiveness of municipal solid waste management systems: An integrated cost-benefit analysis perspective with a financial cost modeling in Taiwan', *Waste Management*, 31(6), pp. 1393–1406. doi: 10.1016/j.wasman.2011.01.016.

Worku, Z. (2016) ‘Predictors of efficiency in municipal waste management in Tshwane municipalities, South Africa’, *Environmental Economics*, 7(3), pp. 45–51. doi: 10.21511/ee.07(3).2016.05.

Xu, Y. *et al.* (2018) ‘Long-term dynamics of leachate production, leakage from hazardous waste landfill sites and the impact on groundwater quality and human health’, *Waste Management*, 82, pp. 156–166. doi: 10.1016/j.wasman.2018.10.009.

Xu, Y. and Chen, Y. (2015) ‘Leaching heavy metals in municipal solid waste incinerator fly ash with chelator/biosurfactant mixed solution’, *Waste Management and Research*, 33(7), pp. 652–661. doi: 10.1177/0734242X15592276.

Yu, Y. *et al.* (2018) ‘Effects of ambient air pollution from municipal solid waste landfill on children’s non-specific immunity and respiratory health’, *Environmental Pollution*, 236, pp. 382–390. doi: 10.1016/j.envpol.2017.12.094.

Zhang, Y., Huang, G. H. and He, L. (2014) ‘A multi-echelon supply chain model for municipal solid waste management system’, *Waste Management*, 34(2), pp. 553–561. doi: 10.1016/j.wasman.2013.10.002.

Zolnikov, T. R. *et al.* (2018) ‘Ineffective waste site closures in Brazil: A systematic review on continuing health conditions and occupational hazards of waste collectors’, *Waste Management*, 80, pp. 26–39. doi: 10.1016/j.wasman.2018.08.047.

Zurbrügg, C. *et al.* (2012) ‘Determinants of sustainability in solid waste management - The Gianyar Waste Recovery Project in Indonesia’, *Waste Management*, 32(11), pp. 2126–2133. doi: 10.1016/j.wasman.2012.01.011.

CHAPTER 7: MICROPLASTICS CONTAMINATION AND ITS IMPACT ON FOOD SAFETY AND ASSOCIATED HEALTH EFFECTS

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Abstract

Microplastics (MPs) are a rapidly emerging food safety threat. The pollution caused by anthropogenic activities and improper waste management exacerbates the magnitude on this global environmental problem. Media such as water, food and air assist MPs to disperse spatially in the environment, thus endangering aquatic and terrestrial ecosystems. Humans are exposed to MPs through a variety of exposure pathways, i.e., ingestion, inhalation and dermal contact. Microplastics have been identified in commonly consumed food products such as fish, fruits, vegetables, meat and poultry. Moreover, the main reported hazards include toxic chemical leakage, adsorption of harmful material through biological vectors and physical damage caused by plastic debris. The challenge with assessing of the risks posed by MPs to humans is determining the correlation between MPs and human health outcomes through epidemiologic investigations. Apart from laboratory-controlled research, there have not been substantial results regarding human exposure and health outcomes. Despite the saturated research in the aquatic environment, there is universal consensus on the lack of research on toxicologic studies on humans and the terrestrial food chain. This paper opens a platform for more investigations on the effects of MPs in the food chain and how they impact on food safety.

Keywords: Microplastics, food safety, health effects

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7.1. Introduction

Microplastic pollution and contamination is ubiquitous and multifaceted. It is considered one of the rapidly emerging food safety threats. Not only does it affect the marine environments; the impact is far-reaching and extends to agricultural products such as vegetables, fruits and food animals (Carrasco Silva *et al.*, 2021; Bai *et al.*, 2022). Emerging threats to food safety and security are problematic, because there is usually a minimal regulatory framework in place regarding policies and other statutory laws to guard against dangers that are not fully understood (Rainieri and Barranco, 2019). There is a gap in empirical research regarding the implication of microplastics on human health and toxicologic effects. This area of research needs full attention from public health agencies, considering the magnitude of plastics produced and distributed globally.

Microplastics are minuted polymers, ranging from 1 µm to 5 mm in diameter (Eerkes-Medrano, Leslie and Quinn, 2019; Jin *et al.*, 2021). Research shows that there is not a universal definition for microplastics, although the size and structure have been used as a basis for characterisation (Sun *et al.*, 2020). In addition, their sizes are further classified into nanoplastics for smaller pieces, and mesoplastics and macroplastics for larger pieces (Yang *et al.*, 2022). The International Organization for Standardization has defined nanoplastics as particles ranging from 1 to <100 nm (Domenech and Marcos, 2021). Plastics are synthetic organic polymers created by the process of polymerisation of monomers extracted from hydrocarbons (He *et al.*, 2018; De-la-Torre, 2020). According to De-la-Torre (2020), it has been estimated that over 335 million tons of plastic products were accumulated globally in 2016. The structure and aquaphobic nature of nano plastics and their sizes enable them to be readily bioavailable (Botterell *et al.*, 2019). They can perpetrate biological cells triggering health-related responses such as growth inhibition, behavioural disorders, reproductive dysfunctions, eating disorders, etc. (Carrasco Silva *et al.*, 2021). Plastic particles can be classified into primary and secondary microplastics (Carrasco Silva *et al.*, 2021). The primary MPs are usually in the form of consumer-care products or those used in industrial processes. The secondary MPs are derived from the natural degradation of large plastics in the environment (Fadare *et al.*, 2020).

Municipal solid waste comprises plastic products that are difficult to control, despite authorities devising strategies to minimise pollution. Municipal solid-waste management operations such as transfer stations have been found to be potential sources of releasing MPs into the surrounding environment (Afrin, Uddin and Rahman, 2020; Golwala *et al.*, 2021; Hu *et al.*, 2022). It has been noted that plastic is one of the biggest anthropogenic pollutants globally. Furthermore, it accounts for 80% of the sea's waste (Carrasco Silva *et al.*, 2021). The constant degradation of large plastics generate microplastics and nanoplastics that are eventually spread through media such as water, air and land (Domenech and Marcos, 2021; Bashir and Hashmi, 2022). The use of polymer materials and its production have increased significantly over the years, due to the demand of convenient and easy-to-use products. This has led to mass production of materials that are not easily biodegradable. Although greener methods and other low-cost interventions such as bioremediation techniques have been devised, the magnitude of the pollution remains overwhelming.

The purpose of this paper is to present the major developments regarding microplastic contamination of food sources and the associated human health effects. Moreover, this review aims to understand the polymer types, morphology and how they interact with the environment. Lastly, it explores future direction of research in risk assessments and potential public health interventions.

7.2 Research trends overview in microplastic research

Microplastic research has been growing significantly in recent years. The study of microplastics came to prominence in 2001, despite earlier publication in the 70s (Yuan *et al.*, 2022) Literature is saturated in the marine environments, ecosystems and wastewater pollution (Qin *et al.*, 2020; Zhang *et al.*, 2020). A preliminary scan of literature was conducted to give an overview of research trends in the last five years. The literature search was completed using the Web of Science core collection databases (WoS). The WoS has been found to be reputable in documenting scientific studies across different disciplines (Li, Rollins and Yan, 2018; Secinaro and Calandra, 2021). The following search string was used: ("microplastics in food*") OR (microplastic pollution and health effects) OR ("Types of microplastics*") OR (microplastic pollution). Exclusions encompassed early-access papers, conference proceedings and book chapters. The information was processed using VOSviewer version 1.6.15 software for mapping and visualization purposes (Van Eck and Waltman, 2010). This software was used to analyse the citation of documents by countries (Meng *et al.*, 2020; Lebelo and Masinde, *et al.*, 2021).

Figure 7.1 shows a significant increase in research relating to MPs in the last five years. Most researchers allude this fact to the rise in interest to understand the drivers of pollution and human health consequences. The sharp decline in 2022 is possibly linked to the incomplete year. The People's Republic of China (28%) has been dominant regarding the research outputs, followed by the United States of America (12.4%), as demonstrated in Figure 7.2. Seventy-eight percent (78%) of the analysed research outputs are from the field of Environmental Science and Ecology, followed by Marine Freshwater Biology (19.9 %), as denoted in Figure 7.3. This proves that current research is still gravitating towards water pollution sources and the general environment. As demonstrated by many researchers, more studies on human health effects and risk assessments need to be undertaken. The bibliometric network of the co-occurrence of the keywords demonstrates the keywords used in MP research (Figure 7.4). The size of the circle depicts the number of co-occurrences. The bigger the circle, the more the words appear together in publications. The thickness of the lines and proximity of the circles represent the strength of the link between keywords. The picture shows that there is a strong link between "ingestion", "pollution" and "microplastics". Table 7.1 summarises the most-cited and prominent publications in MPs research.

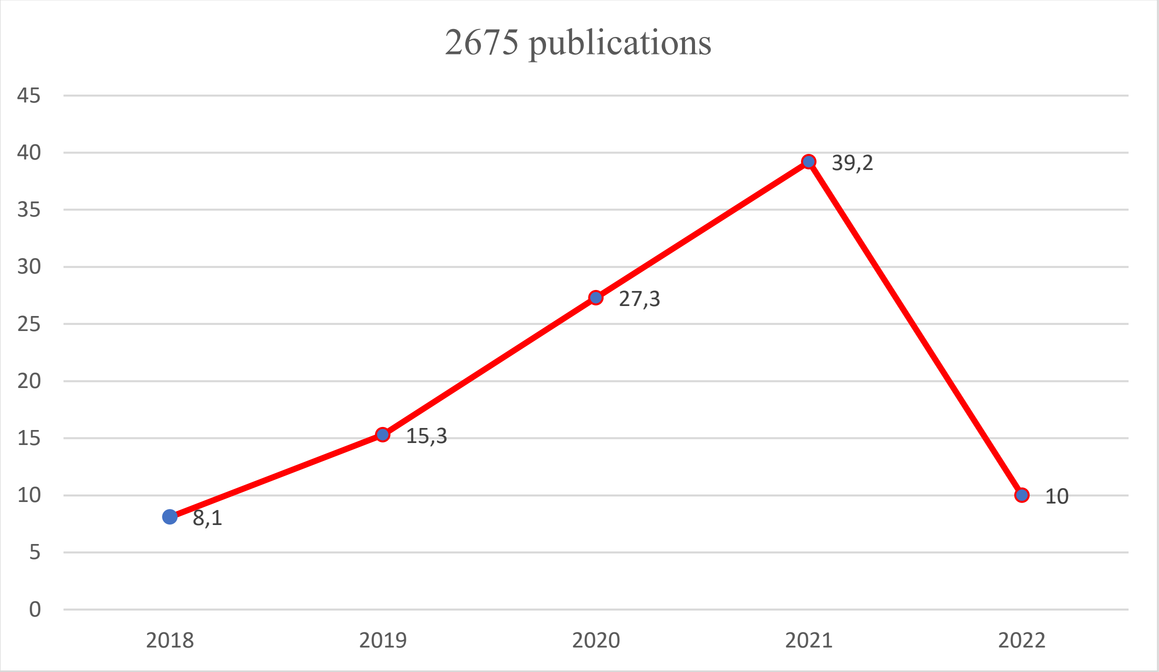

Figure 7.1: Publications in the last 5 years, searched on 28 May 2022 using WoS databases.

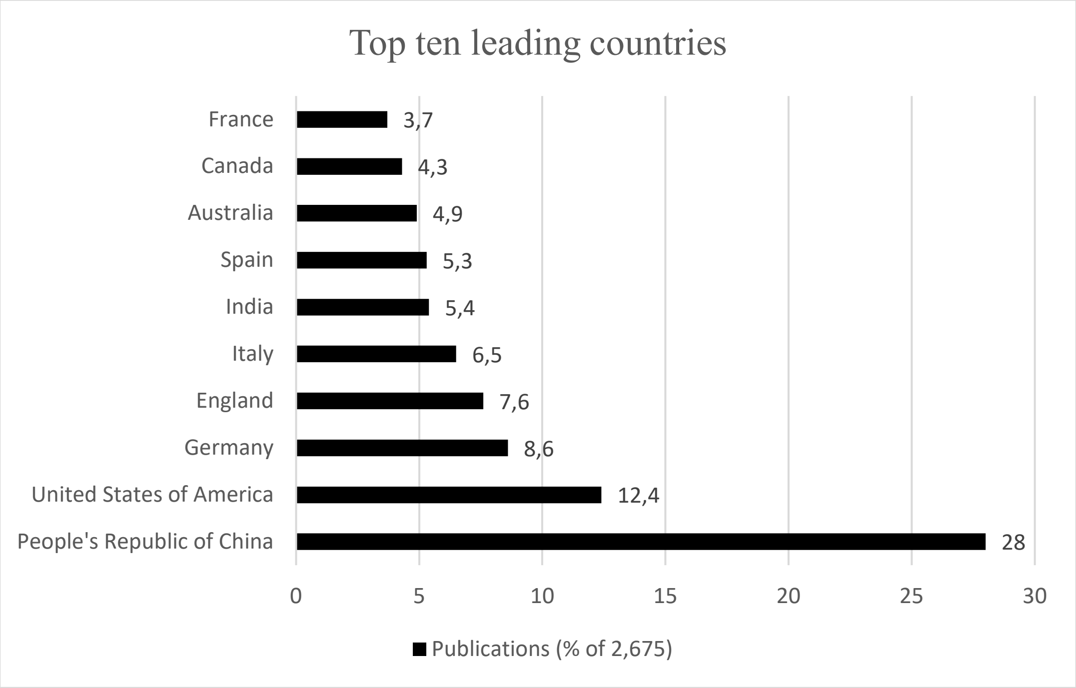

Figure 7.2: Top 10 leading countries in microplastic research.

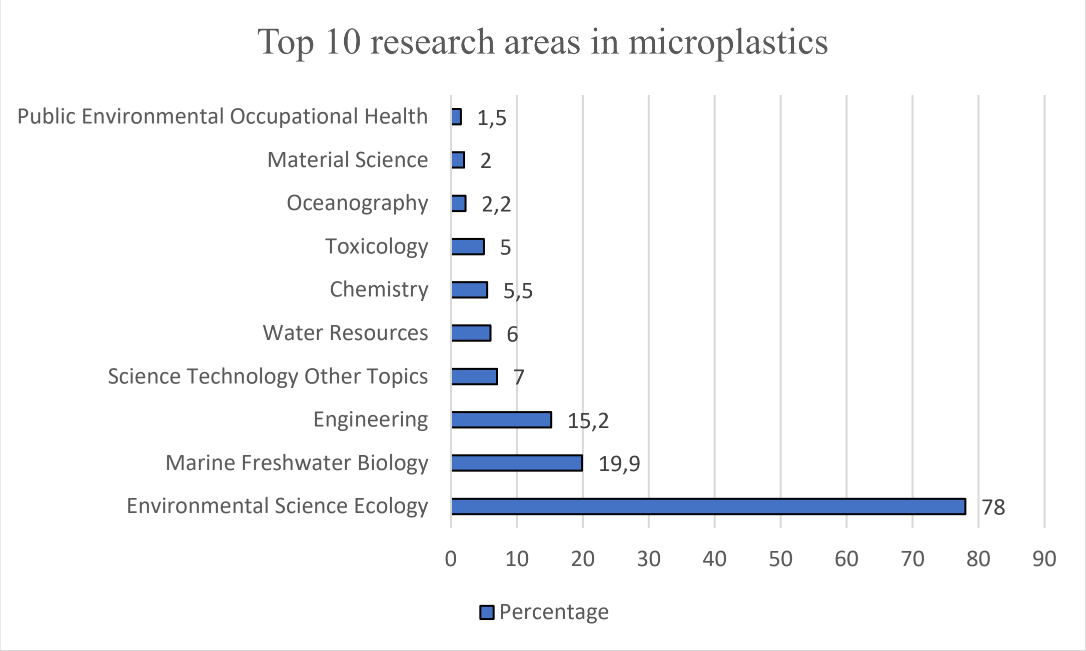

Figure 7.3: Top 10 research areas in microplastic research.

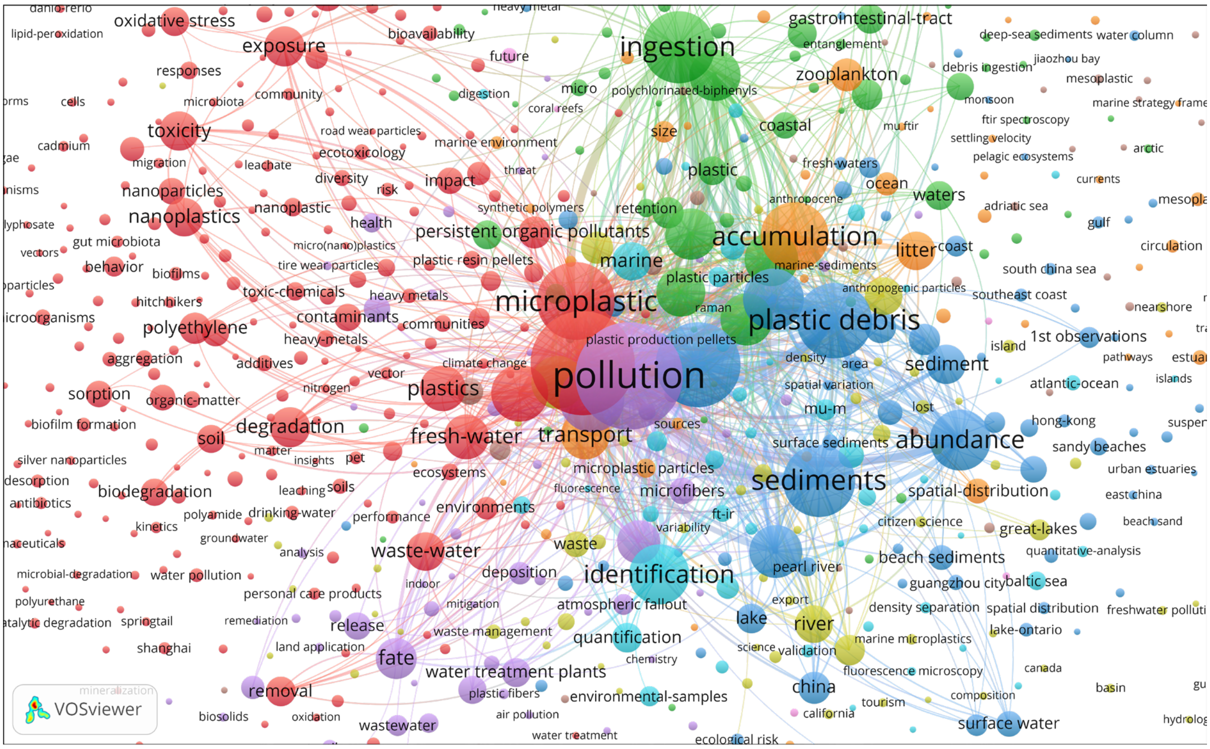

Figure 7.4: Bibliometric network showing the co-occurrence of keywords.

Table 7.1: Summary of top 10 cited papers in microplastic research the last 5 years.

Data collected from the Web of Sciences search engine on 28 May 2022. Search string= (“microplastics in food*”) OR (microplastic pollution and health effects) OR ("Types of microplastics*") OR (microplastic pollution).

	Title of publication	Major findings	Citations	References
1.	Emerging threats and persistent conservation challenges for freshwater biodiversity.	Freshwater biodiversity is constantly threatened by pollutants of different origins. Notably, the persistent pollutants and emerging threats which are intensifying year by year. Microplastic pollution is counted among the 12 studied threats to biodiversity. Effects range from the disturbance of living organisms to ecological degradation. This can present research and policy transformation opportunities to manage new and emerging threats.	705	(Reid *et al.*, 2019)
2.	Microplastics in freshwaters and drinking water: Critical review and assessment of data quality	The review paper covered studies researching MPs in drinking water. From the studied water sources (rivers, lakes, tap water, bottled water, etc.), the study revealed that MPs were frequently detected in freshwaters and drinking water. Moreover, 50 of the reviewed studies showed a need for improved MP sampling, analysis, and quality assurance. Despite the body of research in understanding the types of MPs, PVC remains the most sought-after plastic due to global demand. The finding that is consistent with most studies is that human risk assessments need to be at the forefront of exposure assessments.	548	(Koelmans *et al.*, 2019)
3.	Microplastics as an emerging threat to terrestrial ecosystems	This paper presents the toxicity of nano plastics and their global impact on terrestrial systems. Further, the key drivers of contamination and chemical properties of the pollutants are highlighted. Further highlights indicate how MPs potentially affect	545	(De Souza Machado *et al.*, 2018)

		the soil chemistry, living organisms and torrential fungi. Microplastics present a threat to terrestrial systems and systematic interventions are recommended.		
4.	Are We Speaking the Same Language? Recommendations for a Definition and Categorization Framework for Plastic Debris	This paper proposes a framework for the classification of microplastics due to the inconsistencies in standard definitions and sizes. Debates in the classifications range from composition to solid state, and solubility. The proposed framework aims to encourage agreements on definitions regarding colours, size, criteria and origin.	533	(Hartmann *et al.*, 2019)
5.	Atmospheric transport and deposition of microplastics in a remote mountain catchment	Samples collected over five months showed the presence of wet and dry atmospheric deposits of MPs. The movement of air showed that MPs in the air could travel over 95 kilometres. This demonstrates that even isolated and sparsely located communities can be affected by MPs travelling through the air medium.	522	(Allen *et al.*, 2019)
6.	Microplastic particles cause intestinal damage and other adverse effects in zebrafish *Danio rerio* and nematode *Caenorhabditis elegans*	Five common types of microplastics were studied (polyamides, polyethylene, polypropylene, polyvinyl chloride, and polystyrene). PVC microplastics were found to be among the major causes of intestinal damage, including cracking of villi and splitting of enterocytes. In addition, it was discovered that MPs reduce calcium levels, which is a key factor in intestinal damage and oxidative stress.	466	(Lei *et al.*, 2018)
7.	Plastics in soil: Analytical methods and possible sources	The quantification and identification of plastic in soil are vital in ecological studies. This ensures that there is sufficient data to measure the quality of soil in relation to the role it plays in crop production and reliant organisms. The poor quality of soil can be attributed to various factors such as sewage and wastewater used for irrigation purposes. Plastics have been found in additional sources such as dumping spots, regular littering along the roadside, etc. A recommendation is made on studying the fate of synthetic plastics in soils.	421	(Bläsing and Amelung, 2018)

8.	An overview of microplastic and nanoplastic pollution in agroecosystems	This paper discusses the pivotal role of agroecosystems and the impact of nanoplastic pollution on the environment. There is room for future studies to elucidate and provide evidence of the exposures in the food supply chain to further understand the impact of MPs on the ecosystem and human interaction.	399	(Ng *et al.*, 2018)
9.	Trophic transfer of microplastics and mixed contaminants in the marine food web and implications for human health	Microplastic is transferred primarily through ingestion in the food web. Human health concerns include reactions in several body systems such as the digestive system, nervous system, circulatory system, and others. Even though marine food webs have been extensively researched, there is potential growth in studies addressing potential human health. An important observation in this study is the assertion that more human studies need to be conducted on human health effects in relation to controlled studies with model organisms.	396	(Carbery, O'Connor and Palanisami, 2018)
10.	Future scenarios of global plastic waste generation and disposal	An estimation of between 60 and 99 million metric tonnes of microplastic waste was produced worldwide in 2015. Moreover, it was projected that the burden could triple by 2060 if the *status quo* remains. It is recommended that developed nations set diligent plans to manage their waste and developing nations should be given support to reduce the burden of pollution. In addition, water sources are touted as the major pathways of plastic pollution.	393	(Lebreton and Andrady, 2019)

7.3. Type and toxic effects of microplastics

The widely used polymers are epoxy resins, fluoropolymers, polyolefins, polystyrene, polyurethanes (PUR), polystyrene (EPS) (Domenech and Marcos, 2021), polyvinylchloride (PVC) (Eerkes-Medrano *et al.*, 2019; Muncke *et al.*, 2020; Lebelo, Malebo, *et al.*, 2021; Yang *et al.*, 2022), polyethylene (PE), polyethylene terephthalate (PET) and polypropylene (PP) (He *et al.*, 2018). Further research has shown that microplastics are capable of adsorbing chemical pollutants such as heavy metals, polychlorinated biphenyls (PCB), aromatic hydrocarbons (PAH) and some pesticides in traceable quantities (De-la-Torre, 2020). A study conducted in the Changjiang Estuary and the adjacent East China Sea showed that PVC is the most important pollution risk, according to the risk assessment conducted. The study aimed at providing a preliminary understanding of surface water pollutants in the form of MPs (Xu *et al.*, 2018). However, the pollution load index showed that the area was not severely polluted by MPs.

Plastics are persistent pollutants due to their longevity in the environment. Upon ingestion, they are known to be potentially hazardous. It has been postulated that human health may be affected by the physicochemical property of microplastics. This could be due to some particle sizes such as microfibres being comparatively more hazardous microplastic types to humans (Jin *et al.*, 2021; Ebrahimi *et al.*, 2022; Yang *et al.*, 2022). Researchers have documented health hazards relating to exposure to microplastics. Three main health hazards have been reported to be caused by microplastics. toxic chemical leakage, adsorption of harmful material through biological vectors (Carbery *et al.*, 2018; Xi *et al.*, 2022) and physical damage as a result of plastic debris (Boelee *et al.*, 2019; Hu *et al.*, 2019; Yang *et al.*, 2022; Yuan *et al.*, 2022). In the food chain, microplastics introduce the spread of pathogenic microorganisms (Yang *et al.*, 2022).

7.4. Microplastics as vectors

Li *et al.* (2020) revealed that the microplastics studied had a significant concentration of heavy metals (nickel, iron, manganese and copper). Essentially, this shows that contaminated sources such as rivers can translocate contaminants. Heavy metals would need to be adsorbed to the bioavailable polymers (Li *et al.*, 2020). The mechanism for transporting of heavy metals by MPs is promoted by changes in the polymer. The key drivers of this change are the atmospheric agents and the surface area of the MP (Campanale *et al.*, 2020). The degradation process is thus accelerated through the stimulation of anionic activity that creates an interaction of MPs and heavy metals (Wang and Yuan, 2018; Wang *et al.*, 2018). A study by Kutralam-Muniasamy *et al.* (2020) using electron microscopy energy dispersive spectroscopy (SEM-EDS) shows the presence of heavy metals such as iron, lead, tin, etc. in the micropores and surfaces of MPs prevalent in branded milk. This shows the ubiquitous nature of MPs, even in the dairy industry, where utmost food safety should be prioritised.

The phenomenon of bioaccumulation and the relevance of environmental contaminants are interesting. Reports show that higher consumers in the food chain can transfer contaminants to the least in the food chain. This raises a question about the possible effect of organic and inorganic material being transferred to small organisms in aquatic environments (Kurniawan *et al.*, 2022). Furthermore, research shows that some persistent organic pollutants and polychlorinated biphenyls are hydrophobic. These characteristics make them efficient vectors for harbouring substances when environmental conditions are favourable (Gerdes *et al.*, 2019). This means that MPs have direct and indirect exposure routes as vectors. Examples are the settling of MPs on food whilst harbouring pathogenic materials or trace elements such as heavy metals, and the release of harmful compounds through migration to the food.

Agricultural systems are on the receiving end of a variety of pollutants. Most food chains are formed from the base of terrestrial plants. Therefore, this may result in the disturbance of many trophic levels. Microplastics are known to have the capability to penetrate the seed, root, culm, leaves and fruit plant cells, depending on their size and type (Oliveri Conti *et al.*, 2020). In addition, a study on the *Arabidopsis thaliana* plant shows that nanoplastics can translocate in shoots and accumulate in the roots of the plants, depending on their surface charge (Sun *et al.*, 2020). Moreover, nanomaterials may be absorbed through the roots of the plants through endocytosis when the appropriate sizes of nanomaterials are translocated. The number of MPs in the plant can be determined by the size of the root system and age. In their study, Oliveri Conti *et al.* (2020) reveal that the surface area and moisture content of the carrot's roots significantly increase the likelihood of the adsorption of nanomaterials. Essentially, most MPs are saturated in the soil-plant system. Settling air may contain MPs which eventually settle on the leaves of the plants, thus potentially inhibiting photosynthesis, transpiration, protein synthesis and response mechanisms such as tropisms (Jia *et al.*, 2022; Xi *et al.*, 2022).

7.5. The aquatic environment and animals

Studies are showing that sea salt is contaminated with MPs in most parts of the world. Such contamination is observed on continents such as America, Europe, Asia, etc. (Jin *et al.*, 2021). Water, like salt, is universally used for a plethora of functions. Not only is water consumed for hydration purposes; but it is also used for cooking, recreation and many sanitary functions. This demonstrates the vastness of exposure routes of MPs using the water medium. The regulation of MPs in seafood has proven to be problematic, regardless of the wealth of evidence proving that the human diet accounts for major contaminants. The major issue is the lack of quantification of contaminants. Furthermore, organisms that are ingested whole are reported to present a greater risk, because their digestive tracts, which contain the ingested contaminants, are not removed (Carbery *et al.*, 2018).

The marine ecosystems are studied extensively, including their food webs. Studies have shown that fish, depending on their geographic location and regional pollution levels, is susceptible to MP contamination. The MPs can be found on the surfaces and the digestive tract and then translocated into the circulatory system (Karami *et al.*, 2018; Kumar *et al.*, 2022). The removal of the digestive tract decreases the risk of direct exposure in humans. However, some organisms such as molluscs are consumed along with the digestive tract, thus triggering dietary exposure (Rubio, Marcos and Hernández, 2020). In their study, Karami *et al.* (2018) investigated the potential presence of MPs across 20 brands of canned sardines and sprats in 13 countries distributed across four continents. They discovered that plastic particles were present in sixteen brands. The contamination was attributed to the translocation of MPs to edible parts, inefficient removal of the gastrointestinal tract, and/or direct contact contamination from the canneries. An important consideration is the critical role fish play in the sustenance of both humans and the ecosystem in general. Fish can be considered the main energy source in certain geographical areas. Thus, its contamination can greatly impact the food chain and regional economies. Whilst more studies focus on fish, it is interesting to note that poultry and livestock might be neglected. Free-range chickens and some food animals ingest a lot of contaminants (Bai *et al.*, 2022). In some parts of the world, they are sold and consumed along with the rough offal, thus increasing the risk or exposure to MPs.

7.6. Impact of microplastics on food safety and agricultural land

The fact that microplastic pollution is everywhere, implies that water sources and farmlands are potentially contaminated. Terrestrial soils account for 4–23 times the amount of MPs discharged in the aquatic environment (Xi *et al.*, 2022). Nonetheless, there are economic reasons for the contamination of water. These reasons include food production, energy production, recreation, etc., which subsequently affect water quality and quantity (Boelee *et al.*, 2019; Li *et al.*, 2020). Literature shows that microplastics have been detected in different food products and daily-use items. Their detection in different areas could be a result of their movement in the atmosphere. Microplastics have been found in seafood, salt, honey, sugar, drinking water, beer, etc. (He *et al.*, 2018; Karami *et al.*, 2018; Revel, Châtel and Mouneyrac, 2018; Fadare *et al.*, 2020). In addition, it has been reported that human beings ingest approximately 0.1–5 g of MPs every week in a variety of exposure routes, with bottled and tap water being the major contributors (Karami *et al.*, 2018). Moreover, the exposure can be approximated to 39 000–52 000 microplastic particles ingested per person per year, based on overall food consumption (Kumar *et al.*, 2022).

Research shows that plants are exposed to MPs in different ways, notably, through organic fertilizers, wastewater, plastics from municipal solid waste, MP aerosols and surface runoff. Edible plants are potentially hazardous due to daily consumption as part of a daily diet. Some parts of the country may be exposed more, due to some plants being considered a staple food. Furthermore, the roots of plants are known to accumulate nano plastics at low levels in the root tips (Sun *et al.*, 2020). Other studies show the presence of MPs in well-known vegetables such as potatoes (*Solanum tuberosum*), lettuce (*Lactuca sativa*), carrots (*Daucus carota*) and fruits (Oliveri Conti *et al.*, 2020).

7.7. Microplastic in the food industry

Crops in the agricultural sector are continually contaminated by polluted water; thus, some MPs are ingested through regular human diets of vegetables and fruits. It is estimated that humans are potentially exposed to about 27 types of micropollutants from irrigation water through the consumption of contaminated fruits and vegetables (Carrasco Silva *et al.*, 2021). Microplastics are known to accumulate on root caps, thus increasing the risk for humans when ingesting their staple root crops such as potatoes, beetroot, onions, carrots, etc. (Boots, Russell and Green, 2019; Kumar *et al.*, 2022). Oliveri Conti *et al.* (2020) demonstrate that the Estimated Daily Intake (EDI) of MPs is lower in agricultural food products in relation to the intake of bottled water in adults and children. However, they allude to the fact that the abundant presence of MPs is still concerning (Oliveri Conti *et al.*, 2020). This just highlights the current research output concerning the need for more robust toxicological studies.

The World Health Organization recommends a Mediterranean diet for the prevention of non-communicable diseases. Moreover, five portions of fruits and vegetables, except some starchy roots, have been shown to improve the health status of people (Oliveri Conti *et al.*, 2020). However, the health benefits of these fruits and vegetables are under threat due to the lack of regulation, standards and assessment of MPs. In the agricultural sector, it has been discovered that technologies such as the use of plastic film have both benefits and problems. It has been proven that plastic film can increase agricultural yield by 20–60% (Fu and Wang, 2019). Further benefits include reduced soil erosion and diseases. However, wear and tear, biological degradation and UV radiation can degrade the plastic, thus causing residual decomposition, which contaminates the soil and ultimately translocates into the food plants. (Blackburn and Green, 2022; Dai *et al.*, 2022)

Some of the contaminants are degraded by biological processes such as biosurfactants (Naughton *et al.*, 2019; Da Silva *et al.*, 2020), however, it is pivotal to note the persistence of plastics in the environment. Food animals also get their source of energy from plants and water that are potentially contaminated. This can result in the ingestion of meat products containing high concentrations of MPs. In their study focusing on the presence of MPs in branded milk, researchers (Kutralam-Muniasamy *et al.*, 2020) recommend that a comprehensive outlook be provided on the investigation of MPs in dairy products. In milk, they recommend that consideration should be given to the milking processes on the farms where extraction is conducted using plastic pies and containers. Essentially, these pipes are a possible source of contamination.

7.8. Food packaging industry as a key driver of exposure

The technological advancement in polymer science has revolutionised the food industry and other related industries (Geueke, Groh and Muncke, 2018; Rist *et al.*, 2018; Sobhani *et al.*, 2020). Low-cost polymers are used extensively to meet the demand for the global food industry. Materials such as polyester, alcohol ethylene and polypropylene are commonly used by manufacturers when packaging food (Guerreiro *et al.*, 2018; Han *et al.*, 2018; Majid *et al.*, 2018). To keep consumers satisfied with the quality of foods, these new technologies are necessary, even though they pose certain food safety risks (Galstyan *et al.*, 2018; Mania *et al.*, 2018; Alamri *et al.*, 2021).

A study by Fadare *et al*. (2020) aimed to investigate the presence and quantity of MPs in new plastic products. In this study, food packaging for fast-food delivery was also analysed. The study revealed that the unintentional residues were from manufacturing processes. This study is supported by Habib *et al.* (2022), who postulate that meat-processing activities can introduce MPs to the food production chain. Habib and co-workers studied plastic cutting boards as a source of MPs in meat. In their study, plastic cutting boards made of polythene were found to be a significant source of commercially sold cold-meat products. This contamination occurs as a result of degradation and wear and tear due to the frequency of use. Furthermore, thorough washing of the meat, which is not universally practised, reduces the amount number of MPs on the meat. The hydrophobic surface of MPs also plays a role in the formation of biofilms and microbial colonization. These present a breeding environment for pathogenic microorganisms such as *Vibrio* species, which could potentially cause foodborne diseases of outbreak magnitude (Blackburn and Green, 2022).

It can be deduced that there is room for technological advancement in polymer science where materials with stability can be produced to limit the number of detectable debris and residues (Fadare *et al.,* 2020). Studies show that ingesting bottled water significantly increases exposure to MPs in relation to food, especially if the bottle is recyclable. This is likely due to normal wear and tear, misuse or failure to read manufacturer instructions (Kumar *et al*., 2022). Interestingly, relatively fewer MPs have been detected in groundwater, as reported by Kumar and colleagues. It is possible that in the reported studies, the MPs had not leached into groundwater sources, or the amount of pollution in the areas was relatively less.

7.9. Human exposure to microplastics and health effects

Human exposure pathways to microplastics are diverse. However, the main sources of human exposure are ingestion, inhalation and dermal contact. Ingested contaminants can come from drinking water and food that may be contaminated by the water and, in some instances (Revel *et al.*, 2018), atmospheric pollution and the soil (Weber *et al.*, 2019; Weber, Santowski and Chifflard, 2022; Xi *et al.*, 2022). Inhaled contaminants can stem from landfill operations in solid-waste management (Afrin *et al.*, 2020), synthetic rubbers and dust from polymer-manufacturing industries. The human body has mechanisms to control dermal exposure. However, certain exposure factors limit the effectiveness of the innate ability of the body to resist exposure. The skin has sweat glands and hair follicles that can be seen as preventative mechanisms; however, they can play a role in exposure by attracting contaminants. More research studies need to be conducted by MPs on human health effects. As it stands, most researchers rely on model organisms to form hypotheses on potential human health effects. This calls for sufficient resources to be channelled on studies with empirical evidence of human toxicologic studies. Table 7.2 summarises health effects and exposure pathways in both model organisms and human beings.

Table 7.2: Summary of human and model organism health effects and exposure pathways of microplastics.

Human body systems	**Cellular level** **How MPs move about/exposure pathway**	**Specific health effects**	**Reference**
Nervous system	MPs smaller than 110 µm are accessible in the portal vein and organs	Behavioural disorders,	(Carbery *et al.*, 2018; Carrasco Silva *et al.*, 2021; Kumar *et al.*, 2022)
Digestive system	Particles (<150 µm) can be ingested from food and water	Eating disorders, colon cancer	(Carbery *et al.*, 2018; Revel *et al.*, 2018; Rist *et al.*, 2018; Eerkes-Medrano *et al.*, 2019; Carrasco Silva *et al.*, 2021; Kumar *et al.*, 2022; Yuan *et al.*, 2022)
Urinary system	Translocation across membranes	Kidney damage and nephrotoxicity	(Monti *et al.*, 2015; Campanale *et al.*, 2020; Gao *et al.*, 2021; Yang *et al.*, 2022)
Immune system and Lymphatic system	MPs smaller than 110 µm are accessible in the portal vein and organs. Translocation from the gastrointestinal tract to the lymphatic system.	ROS generation increases, endoplasmic reticulum stress increases, antiandrogenic effect, cytotoxicity, and cell apoptosis	(Revel *et al.*, 2018; Padrón *et al.*, 2020; Rubio *et al.*, 2020; Kumar *et al.*, 2022)
Respiratory system	Inhalation of fibres and dust (<150 µm), Translocation across membranes	Oxidative stress: ROS increases. Allergic, alveolitis, asthma, chronic pneumonia, bronchiectasis and pneumothorax.	(Carbery *et al.*, 2018; Rist *et al.*, 2018; Xu *et al.*, 2018; Gao *et al.*, 2021; Kumar *et al.*, 2022)
Endocrine system		Increased body mass index and waist circumference, destroying the homeostasis of thyroid hormones, growth disorder	(Campanale *et al.*, 2020; Lett *et al.*, 2021)

Reproductive system	MPs smaller than 110 µm are accessible in the portal vein and organs	Birth weight in offspring decreases, and it affects pregnancy outcomes, affects adolescent development, and reduced viability.	(Carber *et al.,* 2018; Carrasco Silva *et al.*, 2021; Kumar *et al.*, 2022)
Circulatory system	MPs (<2 µm) exist in human blood. Translocated from the gastrointestinal tract.	Cancer, destruction of lymphocytes	(Carbery *et al.*, 2018; Revel, *et al.*, 2018; Rist *et al.*, 2018; Çobanoğlu *et al.*, 2021; Gao *et al.*, 2021)
Cardiovascular system	MPs smaller than 110 µm are accessible in the portal vein and organs via translocation.	Decrease in the heart rate, and cardiovascular dysfunctions.	(Carbery *et al.*, 2018; Campanale *et al.*, 2020; Lett *et al.*, 2021)
Musculoskeletal system	Exposure occurs through translocation in body cells.	Cytoskeletal loss due to oxidative stress, protein degradation	(Yong, Valiyaveettil and Tang, 2020)
Integumentary system	Dermal infiltration and translocation.	Skin rashes and irritation, allergic reactions	(Carbery *et al.*, 2018; Yong *et al.*, 2020; Kumar *et al.*, 2022)

7.10. Conducive environments for microplastic dispersal

Specific environmental conditions might be conducive to the wide spread of microplastics. Ultraviolet radiation, rainfall, oxidants, wind speed, microbiological degradation and mechanical fracture by hydrolysis are some of the factors that have been reported to affect the breakdown of MPs (Carrasco Silva *et al.*, 2021; Domenech and Marcos, 2021; Bhagat *et al.*, 2022; Kumar *et al.*, 2022). Weber *et al.* (2022) investigated the dispersal of macro- and microplastics on agricultural fields 30 years after sewage sludge application. Their study shows that human activities such as ploughing contribute to the spatial distribution of MPs on arable agricultural land. The persistence of these pollutants was further demonstrated even after 30 years of no sludge-waste pollution. Globally, studies have demonstrated how municipal solid is managed improperly in most saturated countries. Developing nations are affected the most, due to a lack of resources and capacity (Xu and Chen, 2015; Ma and Hipel, 2016). Fadare and co-workers (2022) have noted that research has saturated on understanding the impact of primary MPs. They further assert that the research focus should also cover the secondary sources of pollution. This holds true because it is widely documented that piles of waste are dumped in the environment without remediation.

7.11. Conclusion

This review presents the key arguments on MP contamination and food safety. The trajectory of research suggests that the focus regarding microplastics should be directed towards understanding the direct effects of MPs on human health and the surveillance tools required to monitor the contamination in the food chain. Toxicologic studies are known to be sensitive and difficult due to timelines. This creates a challenge regarding the correlation between MPs and human health outcomes through epidemiologic investigations to assess the risks. To date, no significant study apart from laboratory-controlled research yields any substantial results concerning human exposure and health outcomes. Therefore, there are still gaps regarding the types of chemical toxicants absorbed by MPs and their subsequent human health effects. Historically, policy adoption on persistent pollutants has taken long, due to the chronic effects of illnesses and the lack of immediate results of human health deterioration. More studies should be conducted in the food industry to link MPs' exposure and human health. Studies show that human biomonitoring is pivotal in elucidating the environmental health risk assessment of MPs. However, there is an insufficient body of knowledge on studies with human subjects. Nonetheless, research shows that there is an adequate body of scholarly work that may facilitate good industrial practices in polymer manufacturing and policy development by government agencies in environmental and public health interventions.

7.12. References

Afrin, S., Uddin, M. K. and Rahman, M. M. (2020) ‘Microplastics contamination in the soil from Urban Landfill site, Dhaka, Bangladesh’, *Heliyon*, 6(11). doi: 10.1016/j.heliyon.2020.e05572.

Alamri, M. S. *et al.* (2021) ‘Food packaging’s materials: A food safety perspective’, *Saudi Journal of Biological Sciences*, 28(8), pp. 4490–4499. doi: 10.1016/j.sjbs.2021.04.047.

Allen, S. *et al.* (2019) ‘Atmospheric transport and deposition of microplastics in a remote mountain catchment’, *Nature Geoscience*, 12(5), pp. 339–344. doi: 10.1038/s41561-019-0335-5.

Bai, C. L. *et al.* (2022) ‘Microplastics: A review of analytical methods, occurrence and characteristics in food, and potential toxicities to biota’, *Science of the Total Environment*, 806, p. 150263. doi: 10.1016/j.scitotenv.2021.150263.

Bashir, A. and Hashmi, I. (2022) ‘Detection in influx sources and estimation of microplastics abundance in surface waters of Rawal Lake, Pakistan’, *Heliyon*, 8(3), p. e09166. doi: 10.1016/j.heliyon.2022.e09166.

Bhagat, K. *et al.* (2022) ‘Aging of microplastics increases their adsorption affinity towards organic contaminants’, *Chemosphere*, 298, p. 134238. doi: 10.1016/j.chemosphere.2022.134238.

Blackburn, K. and Green, D. (2022) ‘The potential effects of microplastics on human health: What is known and what is unknown’, *Ambio*, 51(3), pp. 518–530. doi: 10.1007/s13280-021-01589-9.

Bläsing, M. and Amelung, W. (2018) ‘Plastics in soil: Analytical methods and possible sources’, *Science of the Total Environment*, 612, pp. 422–435. doi:

10.1016/j.scitotenv.2017.08.086.

Boelee, E. *et al.* (2019) 'Water and health: From environmental pressures to integrated responses', *Acta Tropica*, 193, pp. 217–226. doi: 10.1016/j.actatropica.2019.03.011.

Boots, B., Russell, C. W. and Green, D. S. (2019) 'Effects of Microplastics in Soil Ecosystems: Above and below Ground', *Environmental Science and Technology*, 53(19), pp. 11496–11506. doi: 10.1021/acs.est.9b03304.

Botterell, Z. L. R. *et al.* (2019) 'Bioavailability and effects of microplastics on marine zooplankton: A review', *Environmental Pollution*, 245, pp. 98–110. doi: 10.1016/j.envpol.2018.10.065.

Campanale, C. *et al.* (2020) 'A detailed review study on potential effects of microplastics and additives of concern on human health', *International Journal of Environmental Research and Public Health*, 17(4). doi: 10.3390/ijerph17041212.

Carbery, M., O'Connor, W. and Palanisami, T. (2018) 'Trophic transfer of microplastics and mixed contaminants in the marine food web and implications for human health', *Environment International*, 115, pp. 400–409. doi: 10.1016/j.envint.2018.03.007.

Carrasco Silva, G. *et al.* (2021) 'Microplastics and their effect in horticultural crops: Food safety and plant stress', *Agronomy*, 11(8), pp. 1–17. doi: 10.3390/agronomy11081528.

Çobanoğlu, H. *et al.* (2021) 'Genotoxic and cytotoxic effects of polyethylene microplastics on human peripheral blood lymphocytes', *Chemosphere*, 272. doi: 10.1016/j.chemosphere.2021.129805.

Dai, Y. *et al.* (2022) 'Current research trends on microplastics pollution and impacts on agro-ecosystems: A short review', *Separation Science and Technology (Philadelphia)*, 57(4), pp. 656–669. doi: 10.1080/01496395.2021.1927094.

Da Silva, I. G. S. *et al.* (2020) 'Soil bioremediation: Overview of technologies and trends', *Energies*, 13(18). doi: 10.3390/en13184664.

De-la-Torre, G. E. (2020) 'Microplastics: an emerging threat to food security and human health', *Journal of Food Science and Technology*, 57(5), pp. 1601–1608. doi: 10.1007/s13197-019-04138-1.

De Souza Machado, A. A. *et al.* (2018) ‘Microplastics as an emerging threat to terrestrial ecosystems’, *Global Change Biology*, 24(4), pp. 1405–1416. doi: 10.1111/gcb.14020.

Domenech, J. and Marcos, R. (2021) ‘Pathways of human exposure to microplastics, and estimation of the total burden’, *Current Opinion in Food Science*, 39, pp. 144–151. doi: 10.1016/j.cofs.2021.01.004.

Ebrahimi, P. *et al.* (2022) ‘Investigating impact of physicochemical properties of microplastics on human health: A short bibliometric analysis and review’, *Chemosphere*, 289, p. 133146. doi: 10.1016/j.chemosphere.2021.133146.

Eerkes-Medrano, D., Leslie, H. A. and Quinn, B. (2019) ‘Microplastics in drinking water: A review and assessment’, *Current Opinion in Environmental Science and Health*, 7, pp. 69–75. doi: 10.1016/j.coesh.2018.12.001.

Fadare, O. O. *et al.* (2020) ‘Microplastics from consumer plastic food containers: Are we consuming it?’, *Chemosphere*, 253, p. 126787. doi: 10.1016/j.chemosphere.2020.126787.

Fu, Z. and Wang, J. (2019) ‘Current practices and future perspectives of microplastic pollution in freshwater ecosystems in China’, *Science of the Total Environment*, 691, pp. 697–712. doi: 10.1016/j.scitotenv.2019.07.167.

Galstyan, V. *et al.* (2018) ‘Metal oxide nanostructures in food applications: Quality control and packaging’, *Chemosensors*, 6(2), pp. 1–21. doi: 10.3390/chemosensors6020016.

Gao, M. *et al.* (2021) ‘Effect of polystyrene on di-butyl phthalate (DBP) bioavailability and DBP-induced phytotoxicity in lettuce’, *Environmental Pollution*, 268, p. 115870. doi: 10.1016/j.envpol.2020.115870.

Gerdes, Z. *et al.* (2019) ‘Microplastic-mediated transport of PCBs? A depuration study with Daphnia magna’, *PLoS ONE*, 14(2), pp. 1–15. doi: 10.1371/journal.pone.0205378.

Geueke, B., Groh, K. and Muncke, J. (2018) ‘Food packaging in the circular economy: Overview of chemical safety aspects for commonly used materials’, in Holban, A. M. and Grumezescu, A. M. (eds) *Journal of Cleaner Production*. Switzerland: Elsevier Ltd, pp. 491–505. doi: 10.1016/j.jclepro.2018.05.005.

Golwala, H. *et al.* (2021) 'Solid waste: An overlooked source of microplastics to the environment', *Science of the Total Environment*, 769, p. 144581. doi: 10.1016/j.scitotenv.2020.144581.

Guerreiro, T. M. *et al.* (2018) 'Migration from plastic packaging into meat', *Food Research International*, 109 (December 2017), pp. 320–324. doi: 10.1016/j.foodres.2018.04.026.

Habib, R. Z. *et al.* (2022) 'Plastic cutting boards as a source of microplastics in meat', *Food Additives and Contaminants - Part A Chemistry, Analysis, Control, Exposure and Risk Assessment*, 00(00), pp. 1–11. doi: 10.1080/19440049.2021.2017002.

Han, J. W. *et al.* (2018) 'Food Packaging: A Comprehensive Review and Future Trends', *Comprehensive Reviews in Food Science and Food Safety*, 17(4), pp. 860–877. doi: 10.1111/1541-4337.12343.

Hartmann, N. B. *et al.* (2019) 'Are We Speaking the Same Language? Recommendations for a Definition and Categorization Framework for Plastic Debris', *Environmental Science and Technology*, 53(3), pp. 1039–1047. doi: 10.1021/acs.est.8b05297.

He, D. *et al.* (2018) 'Microplastics in soils: Analytical methods, pollution characteristics and ecological risks', *TrAC - Trends in Analytical Chemistry*, 109, pp. 163–172. doi: 10.1016/j.trac.2018.10.006.

Hu, T. *et al.* (2022) 'Emission of airborne microplastics from municipal solid waste transfer stations in downtown', *Science of the Total Environment*, 828, p. 154400. doi: 10.1016/j.scitotenv.2022.154400.

Hu, Y. *et al.* (2019) 'Current research trends on microplastic pollution from wastewater systems: a critical review', *Reviews in Environmental Science and Biotechnology*, 18(2), pp. 207–230. doi: 10.1007/s11157-019-09498-w.

Jia, H. *et al.* (2022) 'Impact of microplastics on bioaccumulation of heavy metals in rape (Brassica napus L.)', *Chemosphere*, 288, pp. 1–8. doi: 10.1016/j.chemosphere.2021.132576.

Jin, M. *et al.* (2021) 'Microplastics contamination in food and beverages: Direct exposure to humans', *Journal of Food Science*, 86(7), pp. 2816–2837. doi: 10.1111/1750-3841.15802.

Karami, A. *et al.* (2018) 'Microplastic and mesoplastic contamination in canned sardines and sprats', *Science of the Total Environment*, 612, pp. 1380–1386. doi: 10.1016/j.scitotenv.2017.09.005.

Koelmans, A. A. *et al.* (2019) 'Microplastics in freshwaters and drinking water: Critical review and assessment of data quality', *Water Research*, 155, pp. 410–422. doi: 10.1016/j.watres.2019.02.054.

Kumar, R. *et al.* (2022) 'Micro(nano)plastics pollution and human health: How plastics can induce carcinogenesis to humans?', *Chemosphere*, 298, p. 134267. doi: 10.1016/j.chemosphere.2022.134267.

Kurniawan, S. B. *et al.* (2022) 'Practical limitations of bioaugmentation in treating heavy metal contaminated soil and role of plant growth promoting bacteria in phytoremediation as a promising alternative approach', *Heliyon*, 8(4), p. e08995. doi: 10.1016/j.heliyon.2022.e08995.

Kutralam-Muniasamy, G. *et al.* (2020) 'Branded milks – Are they immune from microplastics contamination?', *Science of the Total Environment*, 714, p. 136823. doi: 10.1016/j.scitotenv.2020.136823.

Lebelo, K., Malebo, N., *et al.* (2021) 'Chemical Contamination Pathways and the Food Safety Implications along the Various Stages of Food Production : A Review', *International Journal of Environmental Research and Public Health*, 18(11). doi: https:// doi.org/10.3390/ijerph18115795.

Lebelo, K., Masinde, M., *et al.* (2021) 'The surveillance and prediction of food contamination using intelligent systems: a bibliometric analysis', *British Food Journal*. doi: 10.1108/BFJ-04-2021-0366.

Lebreton, L. and Andrady, A. (2019) 'Future scenarios of global plastic waste generation and disposal', *Palgrave Communications*, 5(1), pp. 1–11. doi: 10.1057/s41599-018-0212-7.

Lei, L. *et al.* (2018) ‘Microplastic particles cause intestinal damage and other adverse effects in zebrafish Danio rerio and nematode Caenorhabditis elegans’, *Science of the Total Environment*, 619–620, pp. 1–8. doi: 10.1016/j.scitotenv.2017.11.103.

Lett, Z. *et al.* (2021) ‘Environmental microplastic and nanoplastic: Exposure routes and effects on coagulation and the cardiovascular system’, *Environmental Pollution*, 291(June), p. 118190. doi: 10.1016/j.envpol.2021.118190.

Li, K., Rollins, J. and Yan, E. (2018) ‘Web of Science use in published research and review papers 1997–2017: a selective, dynamic, cross-domain, content-based analysis’, *Scientometrics*, 115(1), pp. 1–20. doi: 10.1007/s11192-017-2622-5.

Li, W. *et al.* (2020) ‘Heavy metals contamination of sedimentary microplastics in Hong Kong’, *Marine Pollution Bulletin*, 153 (August 2019), p. 110977. doi: 10.1016/j.marpolbul.2020.110977.

Ma, J. and Hipel, K. W. (2016) ‘Exploring social dimensions of municipal solid waste management around the globe – a systematic literature review’, *Waste Management*, 56, pp. 3–12. doi: 10.1016/j.wasman.2016.06.041.

Majid, I. *et al.* (2018) ‘Novel food packaging technologies: Innovations and future prospective’, *Journal of the Saudi Society of Agricultural Sciences*, 17(4), pp. 454–462. doi: 10.1016/j.jssas.2016.11.003.

Mania, I. *et al.* (2018) ‘Traceability in the dairy industry in Europe: Theory and practice’, in *Traceability in the Dairy Industry in Europe: Theory and Practice*, pp. 1–160. doi: 10.1007/978-3-030-00446-0.

Meng, L. *et al.* (2020) ‘Knowledge atlas on the relationship between urban street space and residents’ health-a bibliometric analysis based on vos viewer and cite space’, *Sustainability (Switzerland)*, 12(6). doi: 10.3390/su12062384.

Monti, D. M. *et al.* (2015) ‘Biocompatibility, uptake and endocytosis pathways of polystyrene nanoparticles in primary human renal epithelial cells’, *Journal of Biotechnology*, 193, pp. 3–10. doi: 10.1016/j.jbiotec.2014.11.004.

Muncke, J. *et al.* (2020) ‘Impacts of food contact chemicals on human health: A consensus statement’, *Environmental Health: A Global Access Science Source*, 19(1), pp. 1–12. doi: 10.1186/s12940-020-0572-5.

Naughton, P. J. *et al.* (2019) ‘Microbial biosurfactants: current trends and applications in agricultural and biomedical industries’, *Journal of Applied Microbiology*, 127(1), pp. 12–28. doi: 10.1111/jam.14243.

Ng, E. L. *et al.* (2018) ‘An overview of microplastic and nanoplastic pollution in agroecosystems’, *Science of the Total Environment*, 627, pp. 1377–1388. doi: 10.1016/j.scitotenv.2018.01.341.

liveri Conti, G. *et al.* (2020) ‘Micro- and nano-plastics in edible fruit and vegetables. The first diet risks assessment for the general population’, *Environmental Research*, 187 (May), p. 109677. doi: 10.1016/j.envres.2020.109677.

Padrón, P. *et al.* (2020) ‘Trace Element Levels in Vegetable Sausages and Burgers Determined by ICP-OES’, *Biological Trace Element Research*, 194(2), pp. 616–626. doi: 10.1007/s12011-019-01778-4.

Qin, F. *et al.* (2020) ‘Bibliometric profile of global microplastics research from 2004 to 2019’, *International Journal of Environmental Research and Public Health*, 17(16), pp. 1–15. doi: 10.3390/ijerph17165639.

Rainieri, S. and Barranco, A. (2019) ‘Microplastics, a food safety issue?’, *Trends in Food Science and Technology*, 84, pp. 55–57. doi: 10.1016/j.tifs.2018.12.009.

Reid, A. J. *et al.* (2019) ‘Emerging threats and persistent conservation challenges for freshwater biodiversity’, *Biological Reviews*, 94(3), pp. 849–873. doi: 10.1111/brv.12480.

Revel, M., Châtel, A. and Mouneyrac, C. (2018) ‘Micro(nano)plastics: A threat to human health?’, *Current Opinion in Environmental Science and Health*, 1, pp. 17–23. doi: 10.1016/j.coesh.2017.10.003.

Rist, S. *et al.* (2018) ‘A critical perspective on early communications concerning human health aspects of microplastics’, *Science of the Total Environment*, 626, pp. 720–726. doi: 10.1016/j.scitotenv.2018.01.092.

Rubio, L., Marcos, R. and Hernández, A. (2020) 'Potential adverse health effects of ingested micro- and nanoplastics on humans. Lessons learned from in vivo and in vitro mammalian models', *Journal of Toxicology and Environmental Health - Part B: Critical Reviews*, 23(2), pp. 51–68. doi: 10.1080/10937404.2019.1700598.

Secinaro, S. and Calandra, D. (2021) 'Halal food: structured literature review and research agenda', *British Food Journal*, 123(1), pp. 225–243. doi: 10.1108/BFJ-03-2020-0234.

Sobhani, Z. *et al.* (2020) 'Microplastics generated when opening plastic packaging', *Scientific Reports*, 10(1), pp. 1–7. doi: 10.1038/s41598-020-61146-4.

de Souza Machado, A. A. *et al.* (2018) 'Microplastics as an emerging threat to terrestrial ecosystems', *Global Change Biology*, 24(4), pp. 1405–1416. doi: 10.1111/gcb.14020.

Sun, X. D. *et al.* (2020) 'Differentially charged nanoplastics demonstrate distinct accumulation in *Arabidopsis thaliana*', *Nature Nanotechnology*, 15(9), pp. 755–760. doi: 10.1038/s41565-020-0707-4.

Van Eck, N. J. and Waltman, L. (2010) 'Software survey: VOSviewer, a computer program for bibliometric mapping', *Scientometrics*, 84(2), pp. 523–538. doi: 10.1007/s11192-009-0146-3.

Wang, L. and Yuan, X. (2018) 'Two Types of Flash Drought and Their Connections with Seasonal Drought', *Advances in Atmospheric Sciences*, 35(12), pp. 1478–1490. doi: 10.1007/s00376-018-8047-0.

Wang, X. *et al.* (2018) *Architecture of yolk-shell structured mesoporous silica nanospheres for catalytic applications*, *Dalton Transactions*. doi: 10.1039/c8dt02254b.

Weber, C. J., Santowski, A. and Chifflard, P. (2022) 'Investigating the dispersal of macro- and microplastics on agricultural fields 30 years after sewage sludge application', *Scientific Reports*, 12(1), pp. 1–13. doi: 10.1038/s41598-022-10294-w.

Weber, R. *et al.* (2019) 'Assessment of pops contaminated sites and the need for stringent soil standards for food safety for the protection of human health', *Environmental Pollution*, 249 (May), pp. 703–715. doi: 10.1016/j.envpol.2019.03.066.

Xi, B. *et al.* (2022) 'Environmental behaviours and degradation methods of microplastics in different environmental media', *Chemosphere*, 299, p. 134354. doi: 10.1016/j.chemosphere.2022.134354.

Xu, P. *et al.* (2018) 'Microplastic risk assessment in surface waters: A case study in the Changjiang Estuary, China', *Marine Pollution Bulletin*, 133, pp. 647–654. doi: 10.1016/j.marpolbul.2018.06.020.

Xu, Y. and Chen, Y. (2015) 'Leaching heavy metals in municipal solid waste incinerator fly ash with chelator/biosurfactant mixed solution', *Waste Management and Research*, 33(7), pp. 652–661. doi: 10.1177/0734242X15592276.

Yang, X. *et al.* (2022) 'Environmental health impacts of microplastics exposure on structural organization levels in the human body', *Science of the Total Environment*, 825, p. 154025. doi: 10.1016/j.scitotenv.2022.154025.

Yong, C. Q. Y., Valiyaveettil, S. and Tang, B. L. (2020) 'Toxicity of microplastics and nanoplastics in Mammalian systems', *International Journal of Environmental Research and Public Health*, 17(5). doi: 10.3390/ijerph17051509.

Yuan, Z., Nag, R. and Cummins, E. (2022) 'Human health concerns regarding microplastics in the aquatic environment – From marine to food systems', *Science of the Total Environment*, 823, p. 153730. doi: 10.1016/j.scitotenv.2022.153730.

Zhang, Y. *et al.* (2020) 'Global trends and prospects in microplastics research: A bibliometric analysis', *Journal of Hazardous Materials*, 400, p. 123110. doi: 10.1016/j.jhazmat.2020.123110.

CHAPTER 8: BIOREMEDIATION OF ENVIRONMENTAL CONTAMINANTS AND THEIR IMPACT ON FOOD SAFETY IN THE FOOD PRODUCTION CHAIN

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Abstract

Bioremediation is critical in eliminating and controlling environmental contaminants in the ecosystem. This is crucial in the food industry where pollutants are vast. The industry is moving towards novel sustainable food safety strategies and techniques. Also, the nature-based solution should be at the forefront of innovations in the food industry. This paper focuses on the application of bioremediation techniques on chemical environmental contaminants and how the pollutants enter the food production chain. Moreover, the impact of pollutants and the food safety risks on humans and agricultural land are discussed.

Keywords: Bioremediation, chemical contaminants, food safety, inorganic compounds, heavy metals, antibiotics

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8.1. Introduction

The global demand for food due to the ever-increasing population numbers is a major challenge. Industrialization is a continuing threat to food safety and security because of the increasing chemical pollutants accumulating in the environment. Legislative requirements have been set by the authorities in many countries. However, significant concentrations of hazardous chemical compounds are still detected in the food chain (Baez-Rogelio *et al.*, 2017; Chen *et al.*, 2017; Arora, 2018; Bhat *et al.*, 2018). Consequently, the environment and human health are compromised due to the acute and chronic effects of toxic substances. The implication of such pollution is observed chiefly in agriculture-based countries. This happens due to the technologies introduced in the agricultural sector using pesticides, herbicides and fertilizers to promote agricultural produce (Chiacchierini, Restuccia and Vinci, 2004; Bhat *et al.*, 2018).

Abiotic environmental stresses, which encompass pollution in soils by heavy metals and other environmental contaminants, can decrease agricultural yield due to the toxic effects caused by the soil-plant transfer of pollutants (Dotaniya *et al.*, 2018; Odukoya, Lambert and Sakrabani, 2019b). In addition, they influence the safety and nutritional value of food production significantly in various stages of the food production chain to the consumers. Decontamination through degrading polluted media using microorganisms has been explored as an alternative to the existing chemical solutions. Bioremediation technologies are widely used in water treatment due to their economic viability and low-cost maintenance (Kosaric, 2001; Gupta, Pandey and Pawar, 2016; Pandey *et al.*, 2018; Li, Wang and Zhu, 2019; Song *et al.*, 2019). Therefore, bioremediation is a nature-based solution because it encompasses native microorganisms beneficial to environments.

Industrial waste from food processing activities can cause health hazards even though the waste from processing factories is generally deemed non-hazardous (Mata-Alvarez, Macé and Llabrés, 2000; Bhat *et al.*, 2018). The management of waste in the food industry requires sustainable solutions that are environmentally friendly and cost-effective. In food processing plants, biofilms are a major challenge. Biofilms are formed when a cluster of microbial species attach themselves to a surface, thus promoting cell-to-cell interaction to optimize growth (Galié *et al.*, 2018; Drakontis and Amin, 2020). Consequently, they may lead to food contamination, thus causing foodborne disease outbreaks. Various chemical substances have been used effectively to control the formation of biofilms. More recently, innovations have led to the use of bio-solutions as an alternative. The bio-solutions contain microorganisms that can outperform each other regarding energy usage. Some bacteria, such as *Bacillus subtilis,* can produce biosurfactants that are used to disperse *Proteus mirabilis*, *E. coli*, and *Salmonella enterica* (Nitschke and Costa, 2007; Simões, Simões and Vieira, 2010; Naughton *et al.*, 2019).

Research shows that vermitechnology is an efficient technique for reducing the toxicity of pollutants (Bhat *et al.*, 2018). In the past, innovations such as vermicomposting have been used as an effective method of managing organic waste. During vermicomposting, mesophilic microorganisms and earthworms are used to degrade organic residues into a finished product of value. Furthermore, this process produces nutrient-rich manure for crops in the agricultural sector. The microbial enrichment of vermicompost makes it an effective catalyst for food plant growth due to the abundant enzymes and hormones that are required for optimal growth. Ultimately, this assists in the reduction of inorganic fertilizers, which pose a greater danger to the environment and possible contamination of food sources.

8.2. Agricultural farmlands and food safety

Environmental degradation and food safety are among the two critical issues facing the world. In China, these two challenges are complex, in that the effects of one phenomenon directly affect the other (Lu *et al.*, 2015). Environmental pollution affects the soil, water and air, and these elements are vital in food production. The soil serves as a medium for environmental contaminants. Persistent Organic Pollutants (POPs) such as polychlorinated dibenzo-p-dioxins accumulate in the soils from persistent pollutants building up over the years, or during chemical spills. These result in hot spots of pollution, which may be in agricultural land or nearby water sources (Lu *et al.*, 2015; Spina *et al.*, 2018). This type of pollution goes against a declaration signed by state members of the WHO/FAO at the Stockholm convention (2001), where a debate on the use of POPs was discussed together with the global agenda on sustainable development (Weber *et al.*, 2019). Pollution affects the biotic system and the impact manifests in the food chain. The pollution is further exacerbated by the widespread distribution of heavy industries that continue to be a threat to available agricultural land. Therefore, novel technologies need to be introduced to safeguard the health of consumers and the environment at large.

According to Weber *et al.* (2019), 80% of human exposure to persistent organic pollutants is through food. Also, the food derived from food animals such as meat, dairy, chicken and fish is largely the source of exposure. Soil contaminants are taken up by outdoor food animals when they feed. Pollutants such as polychlorinated biphenyls (PCBs) have been reported to be in high concentrations in free-range chickens. This is potentially due to the free-range chickens being able to consume 30 g/day of soil (Weber *et al.*, 2019). Livestock is exposed through their grass feed. Moreover, the exposure chain continues when they are breastfeeding. In other scenarios of contamination, pesticide residues and fertilizers affect agricultural soils by accumulating in the food chain through crops.

Rice and wheat are staple foods globally. Rice in particular forms a significant portion of half of the global population’s dietary intake (Wang, Chu and Ma, 2018; Wang *et al.*, 2019). In China, soil contamination has been enacted due to increased numbers of food safety issues reported in the past. This burden of contamination is attributed to the industrialized regions of the country. Despite legislative interventions in China, the total usage of pesticides and fertilizers increased significantly within the study period of 10 years (1991-2011) (Lu *et al.*, 2015). Therefore, stringent measures should be taken to control and minimize the impact of contaminants on agricultural soils.

8.3. Bioremediation of contaminated environments

Human activities have drawn criticism due to the widespread pollution caused in the air, land, and water. These contaminants, when released into the environment, have toxic effects. Moreover, they can be absorbed through dermal contact, inhalation and ingestion, thus leading to detrimental health complications (Hou and Al-Tabbaa, 2014; Dangi *et al.*, 2019). In a study by Hou and Al-Tabbaa (2014), nearly 90% of China's shallow groundwater is contaminated. Moreover, 37% of the water was contaminated beyond treatment to meet drinking water standards. This was perceived as a direct consequence of the proximity of heavy industries to water sources. Such instances of contamination have led to a revolution of remediation strategies that are largely commercialized, especially in western countries. Over the years, remediation has shifted from merely reducing the pollutants, but also attempting to eliminate the contaminants with the concept of sustainability taking precedence (Hou and Al-Tabbaa, 2014; Amin, 2018).

Bioremediation is defined as the process whereby biological processes are manipulated to reduce or control the impact of pollutants in the environment with the general aim of removing contaminants from the biosphere (Hazen and Stahl, 2006; Frankenberger and Losi, 2015; Azubuike, Chikere and Okpokwasili, 2016; Othmer, 2019). This definition can be classified under various concepts like changing the pH requirements, increasing the concentration of pollutants to make them easily removable, converting toxic material to less toxic forms, and the restoration of polluted environments where active contaminants cannot be removed (Alverez and Illman, 2005; Karigar and Rao, 2011; Othmer, 2019). The process of bioremediation produces specific by-products. Organic compounds are transformed into carbon dioxide, biomass and water (Othmer, 2019). Furthermore, in the water system, excess ammonia or nitrate groundwater can be mineralized into gaseous water. Species that are usually used in bioremediation include bacteria, algae, fungi, plants and invertebrate animals that form part of a complex food web (Gupta *et al.*, 2016). The bioremediation process depends on two key processes, namely bioaugmentation and biostimulation. The process of bioaugmentation includes the increment of microbial populations or the introduction of new species that can degrade substances (Hou *et al.*, 2020). In contrast, biostimulation involves the addition of nutrients to contaminated environments to activate biological activities (Azubuike *et al.*, 2016). These can include adjusting the pH to create a competitive advantage for particular degraders (Alverez and Illman, 2005).

Various methods can be explored in enriching the contaminant-degrading organisms. The most common method in commercial applications is the provision of nutrients to the organisms. This works to catalyse the desired reactions and facilitate the degradation of organic compounds and oxidation of inorganic ions (Othmer, 2019). Also, the nutrients can be combined with biodegradable substrates to increase the rate of absorption and usage of nutrients before they can be washed away from the polluted environment. The addition of substances to the environment can be done in two ways: using biosurfactants and the bioaugmentation process. Biosurfactants essentially increase the bioavailability of the contaminants (Singh, Glick and Rathore, 2018; Araújo *et al.*, 2019), whereas bioaugmentation involves the addition of bacterial species into the environment (Hou *et al.*, 2020). Literature suggests bacterial species have not been effective against hydrocarbon; however, they have been reported to be successful in newly contaminated environments (Li *et al.*, 2019; Othmer, 2019).

The main benefit of bioremediation is to maintain environmental integrity by allowing natural processes to take place. However, in some instances, there is a need for the stimulation of the process through a process called intrinsic bioremediation and natural attenuation (Othmer, 2019). The other advantage is that the bioremediation process is generally economically viable, compared to other alternate options such as physical and chemical remediation. Moreover, it is a sustainable solution in that the residual concentrations, though detectable in some instances, may not have significant or no environmental impact. To achieve remediation, various techniques and technologies can be applied to partially remove or eliminate the pollutant. A combination of physical and bioremediation strategies can be used, depending on the type of pollutant and the extent of the pollution (Alverez and Illman, 2005).

8.3.1. Types of bioremediation methods

Azubuike *et al.* (2016) discuss different types of bioremediation techniques and their relatively low cost and practicality. In support, Kaushal *et al.* (2018) unfolded the process of bioremediation as invented by George M. Robinson as economically viable, in the sense that it is relatively low-cost to run and maintain. It uses low-technology techniques that use biological processes to minimize or eliminate the pollutants in the environment (soil and water). Alternatives to bioremediation are facing criticism due to their cost implications, slow processes, and inefficient removal of pollutants. Methods such as electrodialysis, ion exchange, and adsorption have limitations regarding the removal of contaminants such as heavy metals. The process of chemical precipitation encompasses the suspension of particles after the addition of anions. The major criticism is that it is not specific and not sensitive to heavy metals at low concentrations (Kapahi and Sachdeva, 2019).

In a review article titled ‘Bioremediation options for heavy metal pollution, it is stated that the conventional methods of pollutant treatment have limitations and should be substituted with environmentally friendly techniques such as bioremediation (Cabañas-Vargas *et al.*, 2013; Kapahi and Sachdeva, 2019). Two methods, i.e. *In-situ* and *Ex-situ* bioremediation, are elaborated upon at length by Azubuike *et al.* (2016). It was noted that *ex-situ* techniques encompass the removal and digging of contaminants from affected sites and transporting them to controlled environments for treatment (Table 8.1). In contrast, *in-situ* bioremediation techniques include treating the contaminated environments at the site of specific pollution (Amin, 2018). It is important to note that some techniques can be considered either *In-situ* or *Ex-situ*, depending on the site of treatment and the depth of the pollutant (Azubuike *et al.*, 2016).

Table 8.1: Summary of different bioremediation techniques and their application in the food industry

Bioremediation technique	***In-Situ/Ex-situ***	**Applications in the food industry**	**Advantages**	**Disadvantages**	**References**
Biopile-mediated method	*Ex-situ*	Land farming and manure production	Effective biodegradation provides nutrients, temperature, and aeration are controlled. Flexible and shortens remediation time. Treats a large volume of soil in a limited space	Cost of transportation, possible secondary contamination, inefficient when there is a lack of power supply	(Whelan *et al.*, 2015; Azubuike *et al.*, 2016; Ma *et al.*, 2018)
windrows	*Ex-situ*	Land farming and manure production	Higher rate of hydrocarbon removal depending on soil type. Less extensive preliminary assessments	Cost of transportation, possible secondary contamination. Greenhouse gas release due to anaerobic zones in piled soils	(Azubuike *et al.*, 2016; Senthil et al., 2018; Kapahi and Sachdeva, 2019)
Bioreactor method	*Ex-situ*	Manure and fertilizer production	Good control of bioprocess limits (temperature, pH, substrate, contact area, nutrients, etc.)	The volume of polluted soil may be too large, and the cost of manpower and transportation. Cost of the bioreactor	(Alverez and Illman, 2005; Azubuike *et al.*, 2016; Amin, 2018; Krzeminski *et al.*, 2019)
Land farming	*Ex-situ*	Large agricultural land for crops	Low cost and fewer resources are required. Can be used in any climate or location. Accommodates large volumes of polluted soil. Minimal energy requirements and environmental impact	Requires a large operating space. Time-consuming and less efficient	(Boopathy, 2000; Azubuike *et al.*, 2016; Amin, 2018)
Bioventing	*In-situ*	Lightly polluted soils	No excavation is necessary thus saving costs. Can be used to clean up inaccessible areas.	Volatile Organic Compounds (VOCs) can be transferred to the soil as vapour if not controlled. The possible cost of some high-end equipment to improve the process. Not suitable for soils with low permeability.	(Boopathy, 2000; Alverez and Illman, 2005; Azubuike *et al.*, 2016)

Bioslurping	*In-situ*	Groundwater and soil remediation	Reduces treatment, storage, and disposal costs	Difficulty in creating a vacuum on the unstable water table and highly permeable soil	(Azubuike *et al.*, 2016; Kapahi and Sachdeva, 2019)
Intrinsic bioremediation	*In-situ*	Farming land.	Less expensive due to a lack of external forces.	A longer period to attain target levels of contaminant concentration	(Azubuike *et al.*, 2016; Kapahi and Sachdeva, 2019)
Phytoremediation	*In-situ*	Polluted groundwater used for irrigation and polluted soils	Precious metals that bioaccumulate in plants can be recovered. Environmentally friendly, low maintenance costs, large scale operations, prevention of erosion	Longer remediation period, accumulated toxic substances may enter the food chain	(Alverez and Illman, 2005; Azubuike *et al.*, 2016; Thijs *et al.*, 2016; J. Ma *et al.*, 2018; Senthil *et al.*, 2018; Song *et al.*, 2019)

8.4. Application of enzymes and other biological agents in bioremediation

The acceptance of biotransformation as a method of designing efficient routes to target compounds has yielded many benefits in the field of organic chemistry (Loughlin, 2000; Chiacchierini *et al.*, 2004; Leung, 2004; Sutherland and Ralph, 2019). As a result, there is increased competition between the chemical synthesis of compounds and biological alternatives. Enzymes are among the abundantly available substances of microbial origin. Moreover, they play a critical role as metabolic catalysts (Adrio and Demain, 2014). The biotransformation system requires certain conditions for efficient functioning. According to Chiacchierini *et al.* (2004), the following biotransformation system is ideal: firstly, an efficient enzyme production system, which includes a stable non-disease-causing microbial source strain that is readily available. Secondly, an efficient biocatalyst will be used to rest cells and has fewer side reactions. Lastly, a stable biocatalyst will handle the conditions to optimize the reactions.

There is an increasing application of catalase enzyme with prospects of further research and developments in bioremediation. Enzymes can be regarded as biological catalysts that promote the conversion of substrates into products whilst using less energy to stimulate the reaction (Karigar and Rao, 2011). The adaptability of catalase is a characteristic that makes them an effective indicator of bioremediation. This is in consideration of its role in the remediation of crude-oil-polluted soil (Kaushal *et al.*, 2018). In the process of bioremediation, catalase has been proven to provide the oxygen that assists in the breaking down of hydrogen peroxide into oxygen and water during the aerobic bioremediation of wastes. The enzyme breaks down the reactive oxygen species (ROS) to relieve the oxidative stress by the substrate. Essentially, the enzyme serves as a source of oxygen for the microorganisms that require the presence of oxygen for metabolism. Other applications in bioremediation include treating bleaching wastes and as an indicator of the breaking down of hydrocarbons. Further applications of the catalase enzyme extend to the food industry where is used in the processing of cheese, food packaging, and determining milk quality (Kaushal *et al.*, 2018).

Oxygenases are a group of enzymes belonging to a group reductase. Oxygenase enzymes are further classified into monooxygenases and dioxygenases based on the number of oxygen atoms used during oxidation (Boopathy, 2000). These enzymes play a vital role in the breaking down of organic compounds by facilitating their ability to dissolve in liquid substances. Furthermore, they are well known for their remediation qualities in a variety of organic compounds such as pesticides, herbicides, fungicides, and plasticizers (Karigar and Rao, 2011). Other biological agents involved in bioremediation include fungi. According to Karigar and Rao (2011), fungal species are effective in the removal of chlorinated phenolic compounds in the environment in a process called mycoremediation. This happens because fungi are transported to the soil contaminants faster than bacteria due to their filamentous properties (Pandey *et al.*, 2000; Karigar and Rao, 2011; Dotaniya *et al.*, 2018; Spina *et al.*, 2018). However, it is important to note that not all pollutants are readily absorbed by microorganisms.

8.5. Types of contaminants

Contaminants can be classified into two broad categories: organic and inorganic pollutants. Examples of organic contaminants include hydrocarbons, halogenated and nonhalogenated pesticides and herbicides (Frankenberger and Losi, 2015). Inorganic contaminants consist of chemicals such as nitrogen compounds, metals and metalloids. Problems experienced in pesticide and herbicide contamination are due to residues and direct spills to food sources. Whilst some nonhalogenated herbicides and pesticides are resistant to degradation, some are easily degraded and do not accumulate in the soil and food chain. Improper handling practices and storage are major contributors to industrial spills and prolonged contamination (Othmer, 2019). Aerobic and anaerobic degradation are approaches that can depend on the type of chemical compound. Anaerobic degradation usually takes time, compared to the aerobic process. However, complete mineralization is achieved in the absence of oxygen.

The meat and dairy industry uses high volumes of water during daily operations. The organic matter released during slaughtering in the meat industry may contain proteins, fats, pesticides, antibiotics, heavy metals, sanitation agents (disinfecting agents), manure, and microorganisms (Villarroel Hipp and Silva Rodríguez, 2018). These contaminants can seep back into the food chain if left untreated. The industrial wastewater leads back into the irrigation system where it can be used for agricultural purposes (Cecconet *et al.*, 2019). Therefore, there is a need for the treatment of industrial waste due to the potential consequences.

8.6. Bioremediation of heavy metals implicated in the food production chain

The global demand for food must correlate with the population increase to improve the living standards of the population. According to Hou *et al.* (2020), this realization will be a challenge due to agricultural land pollution caused by industrialized countries. Heavy metals are essential agricultural contaminants. Their bioavailability to crop uptake, toxicity and inability to degrade make them a serious concern regarding food safety and security globally (Hou and Al-Tabbaa, 2014; Arora, 2018; Gaur, Narasimhulu and PydiSetty, 2018; Hou *et al.*, 2020). The most common heavy-metal pollutants are mercury, arsenic, lead, chromium and cadmium (Rizwan *et al.*, 2016; Mu *et al.*, 2019; Sher and Rehman, 2019; Wang *et al.*, 2019; Hou *et al.*, 2020). The following are leading sources of soil pollution by heavy metals: surface runoff of mine effluents, sewage sludge, polluted irrigation water, impure fertilizers, aerosols from mining activities, vehicles use, fossil-fuel burning, and others. Figure 8.1 shows how contamination from wastewater reaches the food chain.

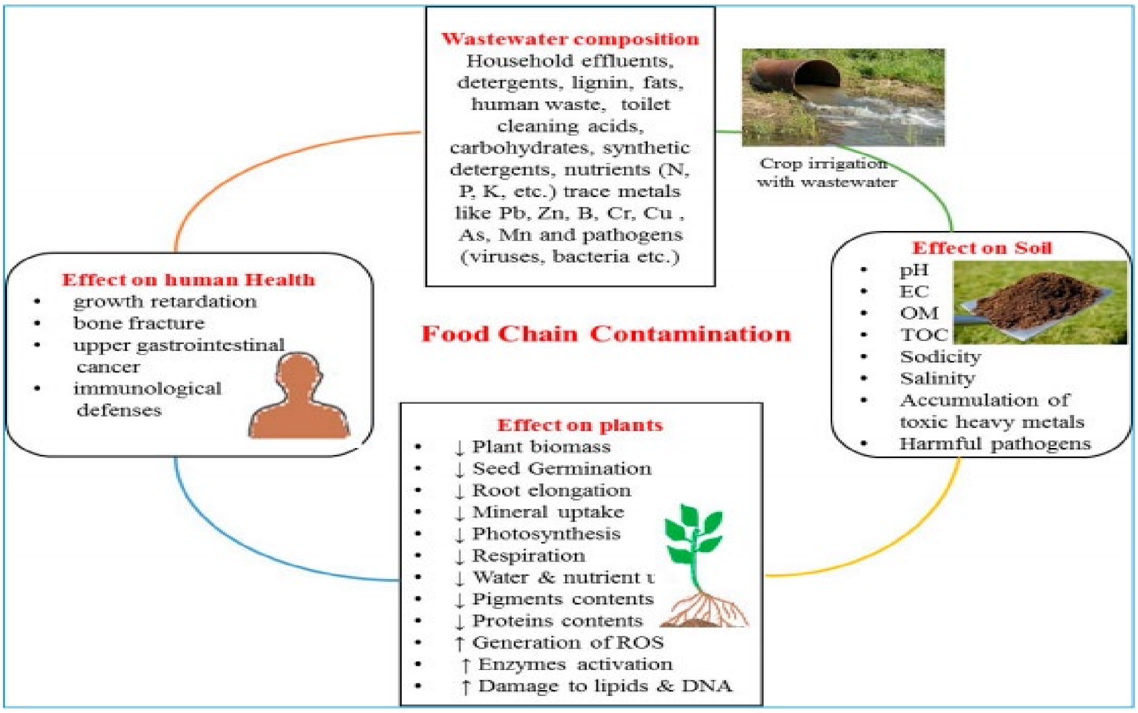

Figure 8.1: The possible food chain contamination by wastewater crop irrigation (Khalid *et al.*, 2018). Open access

Environmental contamination at large has prompted the need for extensive research in effective bioremediation techniques. The effect of heavy metals/metalloids is detrimental to the environment in excess concentrations (Dotaniya *et al.*, 2018). Metalloids/heavy metals are reported to be among the most frequently reported hazardous substances (Frankenberger and Losi, 2015). Various techniques are used to remediate contaminated soil and metal-rich water. However, different contaminants of different substances require different remediating technologies. The aim of remediating heavy metals in water is the total removal of the contaminant. On the contrary, remediating the soil does not remove the contaminant, but it is bound to a matrix through solidification or fixation technologies (Frankenberger and Losi, 2015). According to Frakenberger and Losi (2015), the solidification of soil involves the stabilization of the contaminated matrix by adding plant-based or synthetic compounds. Moreover, this solidification process is designed to decrease the production of leachate in the environment.

Bioremediation essentially uses microorganisms to turn organic substances into less harmful substances (Maikudi Usman *et al.*, 2016; Olasanmi and Thring, 2018). The microorganisms' natural degrading capabilities are optimally used to individualize heavy metals and thus turn them into less toxic substances. The soil is a non-renewable resource and its role is critical in supporting the ecosystem. Also, it is an effective medium for crop production however manmade activities can potentially degrade and contaminate it (Hou and Al-Tabbaa, 2014; Hou *et al.*, 2020). Soil contaminants can enter the human body through inhalation or ingestion of contaminated water, crops, and soil. In the agricultural sector, the biological activities of microorganisms can be used to treat contaminated soil before crops are grown. This happens through the alteration of the pH of the metal facilitated by increasing temperature (Sarubbo *et al.*, 2015).

Bioremediation methods are increasingly used in the food industry to control contamination by heavy metals (Govarthanan *et al.*, 2016). Various species such as bacteria, cyanobacteria, yeasts and algae have been used to control and absorb heavy metals (Massoud *et al.*, 2019; Sutherland and Ralph, 2019). *Saccharomyces cerevisiae* (*S. cerevisiae*) is popular in the food industry for its biosorption capabilities. This species has a high affinity to some metal ions. Therefore, it takes up more metal ions due to its high sorption characteristics. Various researchers such as Negi*,* Mor and Ravindra (2020) have written extensively about heavy metals found in the environment and the opportunities that arise in the research field. Even though extensive research has been conducted on the application of *S. cerevisiae* in the removal of heavy metals in polluted environments, more studies need to focus on its application in the removal of heavy metals in foodstuffs (Massoud *et al.*, 2019; S. Kumar *et al.*, 2019). Figure

8.2 depicts how hazardous heavy metals are transferred from the soil to vegetable plants and various factors influencing the uptake.

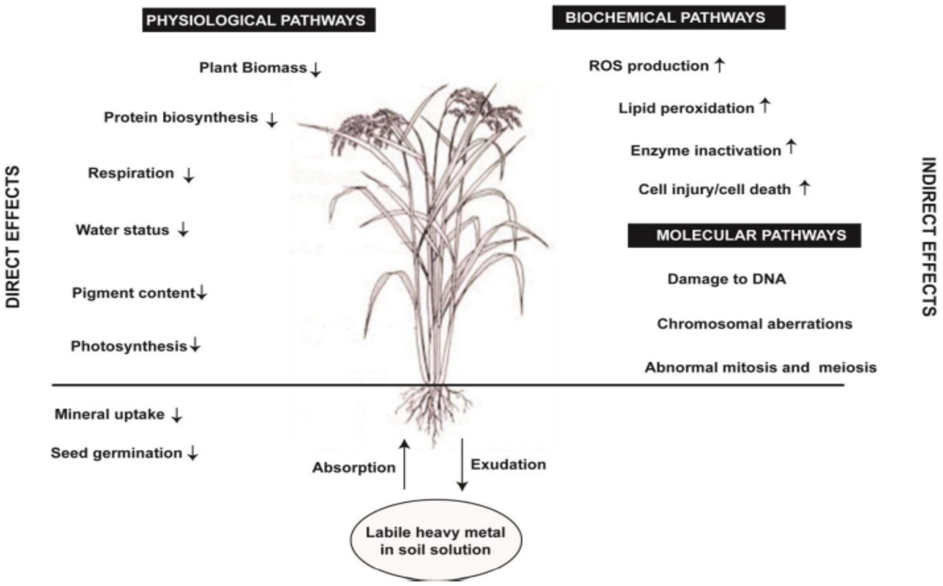

Figure 8.2: The uptake of heavy metals in crops and their impact on crop production (Bhat *et al.*, 2019). Open access

The Mercury (Hg) discharged by industries into water streams can contaminate the water sources and ultimately affect aquatic life. Food such as fish is potentially affected thus posing a risk to human beings upon consumption. The consequences typically include physical impairment or death (Frankenberger and Losi, 2015). The accumulation of mercury in water bodies is believed to be caused by bioaccumulation in the food chain. As a result, species such as fish have been reported to have elevated levels where methylmercury is detected, compared to the surrounding water (Frankenberger and Losi, 2015; Pratush, Kumar and Hu, 2018). Other health effects of mercury are evident in grains treated with mercury-containing fungicides. The main component in mercury remediation in wastewater is the control of pH. The pH affects the bioavailability and solubility of the contaminant through various processes such as redox reactions, pre-treatment processes, hydrolysis, etc. (Kapahi and Sachdeva, 2019). Amongst other toxic heavy metals that may compromise food safety, there is lead (Pb), arsenic (As), cadmium (Cd), and chromium (Cr) (Zhang *et al.*, 2015). Factors such as soil acidification and pH can increase the concentration of cadmium in rice grains. This can be attributed to local mining activities and irrigation with contaminated water. Table 8.2 summarises the selected heavy metals and their impact on human health.

Table 8.2: Selected heavy metals and their impact on human health.

Heavy metals	Route of exposure	Source of exposure	Documented health effects	References
Mercury	Oral ingestion	Contaminated fish/seafood	A neurological disorder, sometimes death, nephrotoxic effects, gastrointestinal complications	(Deb, 2018; Kapahi and Sachdeva, 2019; Thompson and Darwish, 2019)
Lead	Oral ingestion, inhalation	Drinking water, air, grains, and vegetables	Chronic Pb intoxication with low concentrations were found to cause pain, constipation, anaemia, and an increase in hypertension and cardio-vascular diseases in adults, while neuropathological disorders and even learning capacities are affected in children	(Filazi *et al.*, 2017; Bari and Yeasmin, 2018; Ahmad *et al.*, 2019; Kapahi and Sachdeva, 2019; Thompson and Darwish, 2019)
Cadmium	Oral ingestion	Phosphate fertilizers, of seafood and water, milk, fruits	Increased risks for lung, endometrium, urinary bladder problems, neurotoxic effects, breast cancer, vomiting, nausea	(Rizwan *et al.*, 2016; Bari and Yeasmin, 2018; Rehman *et al.*, 2018; Kapahi and Sachdeva, 2019; Mu *et al.*, 2019; Thompson and Darwish, 2019)
Zinc	Oral ingestion	Fish	Respiratory problems	(Bari and Yeasmin, 2018; Rai *et al.*, 2019; Thompson and Darwish, 2019)
Nickel	Oral ingestion	Contaminated food, food processing industries	Can affect renal functioning	(Pratush *et al.*, 2018; Rai *et al.*, 2019)
Arsenic	Oral ingestion	Agricultural pesticides, drinking water, food	Dermatotoxity, lower body weight, fetotoxicity, bone marrow depression	(Rehman *et al.*, 2018; Ahmad *et al.*, 2019; Kapahi and Sachdeva, 2019; Rai *et al.*, 2019; Sher and Rehman, 2019)
Copper	Oral ingestion	Pesticides production and metal piping, contaminated water and food	Stomach and intestinal irritation, liver and kidney complications	(Dotaniya *et al.*, 2018; Pratush *et al.*, 2018)

8.7. Bioremediation of antibiotics in the food industry

Antibiotics are antimicrobial compounds that can be naturally occurring, synthetic, or semi-synthetic (M. Kumar *et al.*, 2019). They can be regarded as “complex molecules with different functional groups in their chemical structures and are divided into several classes” (Cycoń, Mrozik and Piotrowska-Seget, 2019). Throughout history, they have been applied for human, animal and plant health due to their significant antimicrobial properties. The increasing production of livestock and animal feed poses a threat to the environment through antibiotic resistance of bacteria and the increase in the production of antibiotics (Cycoń *et al.*, 2019). This is evident in the trace of antibiotics in food and water systems. Antibiotics are detected in areas where manure is expansively applied and in other natural ecosystems. Besides, some fertilizers encompass animal excreta which may be rich in antibiotics from animal feed. Therefore, the soil binding capacity of fertilizers contaminates the water bodies (Kang *et al.*, 2013; M. Kumar *et al.*, 2019). The typical sources of antibiotics include hospital waste, dairy factories, pharmaceutical industries, animal husbandry, etc. According to Kumar *et al*. (2019), antibiotic residues on surfaces affect a variety of factors such as the aquatic system, soil fertility in agriculture, natural bacterial cycles, and animal production. By implication, the misapplication and lack of control over the usage of antibiotics can severely disturb the ecosystem. This happens due to the capability of antibiotics in attacking non-target organisms. Therefore, for the reasons stated above, bioremediation is a plausible alternative to the physical and chemical remediation strategies which may burden the environmental integrity and threaten sustainability.

Antibiotics are subject to different biotic or abiotic processes in the soil which may encompass degradation or transformation. Some antibiotics are not easily degraded and are persistent in the environment. Examples of persistent antibiotics include tetracyclines, macrolides and fluoroquinolones (Cycoń *et al.*, 2019). Typically, antibiotics get washed up into water streams by rainfall and soil erosion. The resultant outcome that contributes to food contamination is the use of the same polluted water sources in agricultural land. In the soil, antibiotics can be degraded. This happens when some bacteria that can degrade the antibiotics are added to the soil in the right quantities. Cycoń *et al.* (2019) have reported that the strains *Burkholderia*, *Microbacterium*, *Stenotrophomonas*, *Labrys*, *Escherichia*, and *Ochrobactrum* can degrade the following antibiotics: sulfamethazine, penicillin G, erythromycin, tetracycline and doxycycline. The researchers further note that *Microbacterium* species introduced in agricultural soil mineralize the sulfamethazine antibiotics by 44–57%. These results may be largely due to the alteration in the concentration of the antibiotic, the temperature, and the pH of the soil. A study found that increasing ciprofloxacin dosages from 1 to 5 and 50 mg/kg soil reduced the degradation from 75 to 62 within 40 days (Cycoń *et al.*, 2019). These findings may suggest that an increase in antibiotic concentration in the soil may result in high persistence in soils.

In the dairy industry, contamination is prevalent because of limited research on the fate of pollutants. Growth-promoting antibiotics such as chlortetracycline and lincomycin can be detected in dairy effluents, which eventually lead to municipal drains. As a precaution, bioremediation of industrial effluents is highly recommended to minimize further contamination of the environment. The process of bioremediation of antibiotics can be facilitated by the use of species such as *Candida* species and *Escherichia* species. These microorganisms are an ideal option for engineering antibiotics degrading bacteria (M. Kumar *et al.*, 2019).

It has been reported that China is the leading country regarding livestock antibiotic usage with greater than 15 000 tons (M. Kumar *et al.*, 2019). Moreover, in China, the Ministry of Agriculture has set requirements for the prescription of veterinary drugs. This was done to control the over usage of drugs and to address food safety concerns in food animal production (Hu and Cheng, 2016). However, these came with challenges regarding monitoring standards, poor implementation and enforcement of drug-related protocols. Therefore, countries should set strict legislation on the maximum allowable limits for antibiotics in line with international best practices. Similarly, in underdeveloped countries, the use of antibiotics in aquaculture is abused, due to less stringent control measures (Devleesschauwer *et al.*, 2018; Okocha, Olatoye and Adedeji, 2018; Sivagami *et al.*, 2020). Among the consumers of antimicrobials, South Africa, India, Brazil, and Russia have been reported to lead most countries (Okocha *et al.*, 2018). As reported by Sivagami *et al.* (2020), this is detrimental considering that 70–80% of antibiotics used in aquatic farming lead back to the environment. Ultimately, the control of antibiotics requires responsible users to adhere to safety data sheet recommendations, proper handling, and distribution practices (Okocha *et al.*, 2018). Figure 8.3 below depicts how antibiotics enter the food chain. As a consequence, the antibiotics are transferred into the environment through excreta resulting from improper handling practices.

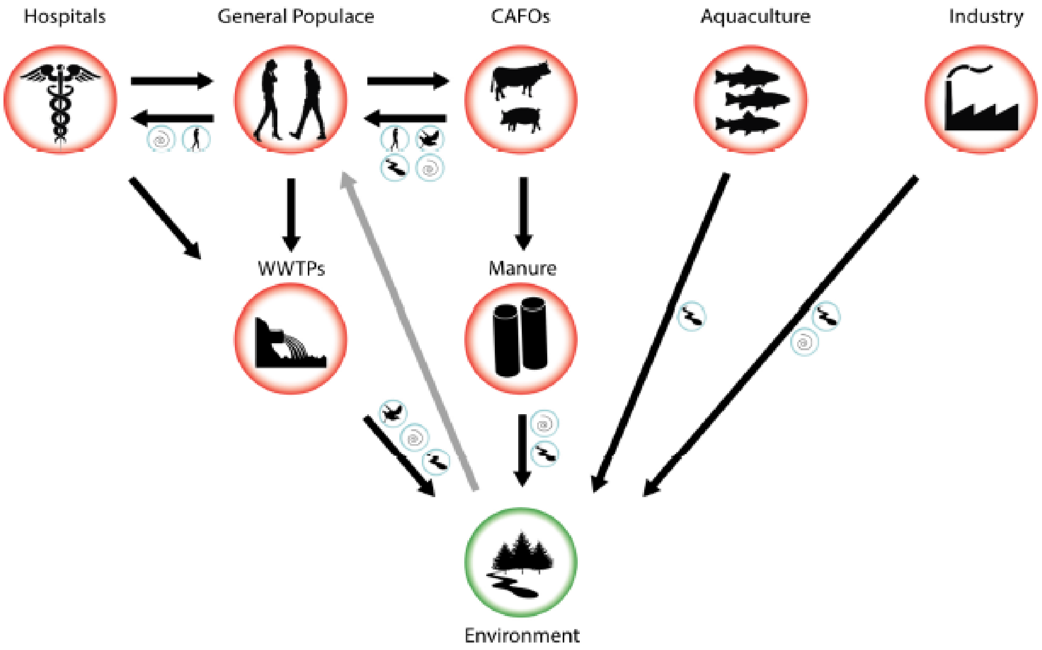

Figure 8.3: Schematic representation of antibiotic-carrying bacteria and antibiotic-resistant genes transmitted to the environment through humans, animal vectors, surface water, wastewater treatment plants (WWTPs) and air (Kraemer, Ramachandran and Perron, 2019). Open access.

8.8. Phytoremediation

Various bioremediation approaches have been deemed acceptable. One amongst many is phytoremediation. Phytoremediation in soil decontamination uses homegrown or imported species of various plants as shown in Figure 8.4. These plants can either be natural or genetically modified (Da Silva *et al.*, 2020; Hou *et al.*, 2020). Employing this approach in bioremediation requires consideration of several factors such as the type of plant species, biogeochemical processes inherent to the plants for optimal growth, soil type and metal speciation. The most commonly studied phytoremediation technique is phytoextraction (Hou *et al.*, 2020). The process of phytoextraction encompasses the extraction of the contaminant by the roots of the plant. Then the absorbed pollutant accumulates in the plant's biomass above ground which is harvested. Various factors inherent to the plants must be considered when selecting the type of plant to be used for phytoremediation.

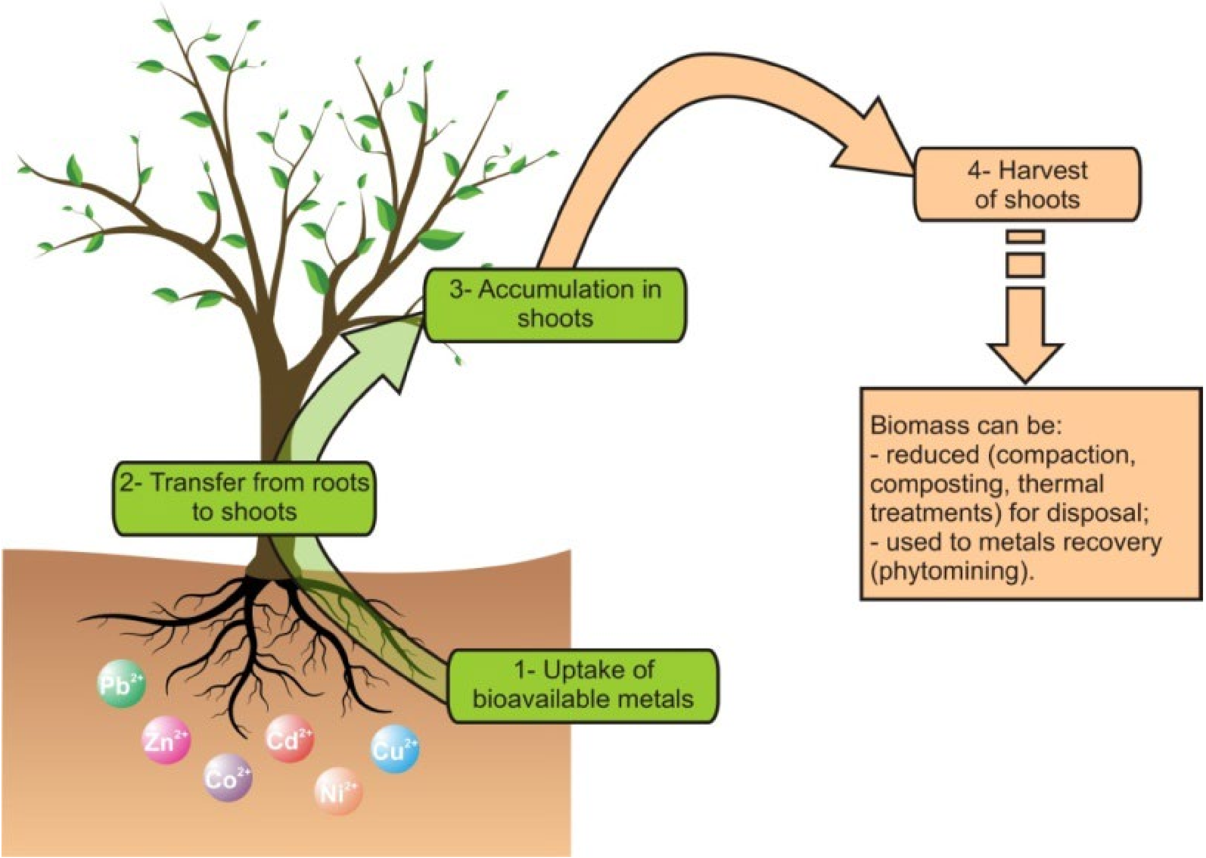

Figure 8.4: An illustration of the phytoremediation process (Favas. J.C *et al.*, 2014). Intech (Open access).

Plants such as eucalyptus and willow are recommended due to their adaptability and the capability to extract a wide variety of heavy metals. Furthermore, another variable to consider in the selection of plants is the growth rate of the plant and capillarity. By implication, the more the plant grows, the higher the chances of fast extraction rates. Heavy metals and metalloids move in the plant through translocation. Essentially, they travel from the roots to the leaves. Ultimately, the contaminants will reach the leaves, seeds and fruits. Food safety is compromised when the contaminant reaches the food chain. Strategies such as phytoremediation can be utilized to address such types of contamination in the environment (Christou *et al.*, 2017).

Phytoremediation of most organic compounds has been reported to largely focus on chlorinated solvents, petroleum hydrocarbons, and explosives (Karigar and Rao, 2011). Crude oil is a natural compound consisting of hydrocarbons and other elements such as nitrogen, oxygen, and sulphur (Kaushal *et al.*, 2018; Odukoya *et al.*, 2019b). This mixture has been a concern due to its harmful impact on the environment and its potential to contaminate water sources and ultimately leach into the food chain. According to Kaushal and co-workers (2018), soil contaminated with crude oil can have a pH of up 8.0. However, it is still uncertain how the composition of the affected plants in agricultural land is influenced (Odukoya *et al.*, 2019b). The oil reduces the availability of phosphorus concentration in the soil which is critical for plant growth. Therefore, the extent of exposure and the specific impact on plants should be studied extensively. Crude oil contamination comes in varying degrees; it can be small or large. The contamination occurs as a result of technical errors, negligence, and storage and transportation faults (Odukoya *et al.*, 2019b). Even though small spills are more common than large spills, the severity depends on the specific environment the pollutant contaminates. Sensitive resources such as agricultural land and water sources are largely exposed due to exposure to petroleum hydrocarbons as a result of crude oil. Odukoya *et al.* (2019b) further reiterate that the movement or migration of spilt oil depends on certain environmental factors and soil properties. The spread of the oil is influenced by the porosity of the soil, density, viscosity and pH (Odukoya *et al.*, 2019a).

In contrast to the studies that have shown the detrimental effects of hydrocarbons on food-producing plants, some studies have shown that the addition of 0.75% *w/w* of crude oil to the soil can improve the growth of soybeans (Odukoya *et al.*, 2019a). However, the researchers found that the observed improvement of the soybeans could be attributed to the bacterial degradation of the hydrocarbons. The growth stimulation could also be attributed to the release of nutrients by the soil (Odukoya *et al.*, 2019b). Further experiments by Odukoya (2019b) have shown that petroleum hydrocarbons at a concentration of ≤10,000 mb/kg total petroleum hydrocarbons affect green leafy vegetables' stomata negatively in such a way that carbon dioxide is not transported efficiently to the leaves for the process of photosynthesis to take place.

8.9. Remediation and management strategies

Various methods of remediation are used to control the number of contaminants in the environment. The most commonly used method is the removal of contaminated topsoil in agricultural holdings; alternatively turnover, or mixing to reduce the effect and the number of contaminants. Bioremediation is one of the methods used to remedy polluted environments. Microbial activity in the soil has been shown to decrease and degrade certain pollutants such as polycyclic aromatic hydrocarbons (PAHs) (Thompson and Darwish, 2019; Ławniczak *et al.*, 2020). Figure 8.5 illustrates the process of the emulsification and desorption of hydrocarbons through the application of biosurfactants.

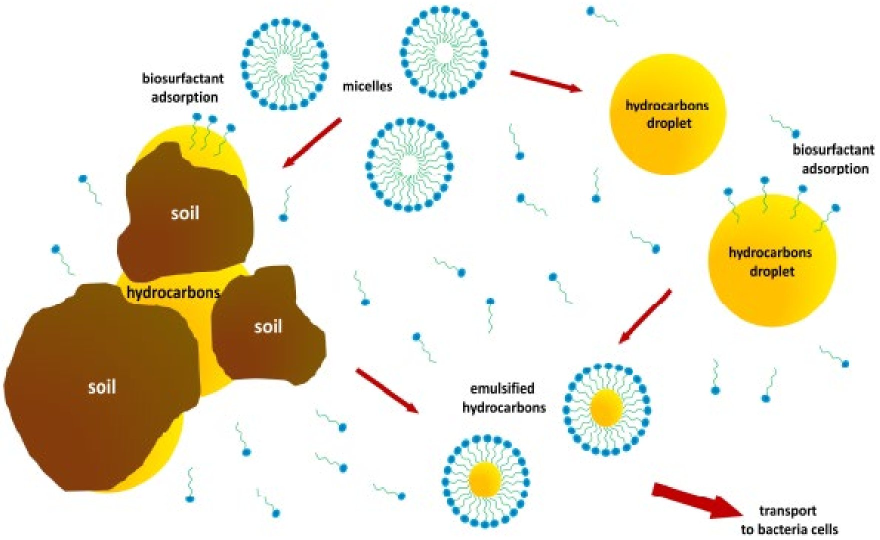

Figure 8.5: A schematic illustration of the desorption and emulsification of hydrocarbons by biosurfactants (Kaczorek *et al.*, 2018). Open access

A comprehensive system needs to be adapted depending on climatic factors and anthropogenic factors. This system will have to consider the following: management of industrial effluents, water irrigation, and sludge application (Rai *et al.*, 2019). Innovative technological strategies need to be established to control the impact of chemical contaminants in the agricultural sector. The use of agro-nanotechnology has been recommended by a variety of researchers globally. Various researchers proposed risk-based assessments using geospatial techniques to locate regions with the highest concentration of metallic contaminants (Rai *et al.*, 2019; Thompson and Darwish, 2019). Further strategies include the strengthening of legislative requirements and policy implementation (Boopathy, 2000). This assists in controlling the type of sites suitable for agricultural activities. Several factors can promote or inhibit the use of bioremediation technologies. The area of human capacity development and research needs to be explored in depth. This is due to the novel techniques and new technologies used in recent times. Therefore, training and development should be an area of focus.

The ever-increasing popularity of organic food products comes with heavy contention. This is regarding the cost of producing organic products concerning cheaper chemically produced options. Reducing the global pollutant footprint is on the global agenda for sustainable development. As a result, many nations are beginning to use adequately treated sewage sludge and wastewater to reduce contamination (Yang *et al.*, 2020). According to Rai *et al.* (2019), treating wastewater reduced metal contamination by 85% in a study conducted in Algeria. Moreover, the researchers advocate the better distribution of arable land. To fully optimize the use of land, they recommend that road-food crops be grown at least 30 m away from the road to reduce contamination by motor-vehicle emissions (Rai *et al.*, 2019).

8.10. Conclusion

his paper was developed on the concept that the process of bioremediation can be used to degrade pollutants to ensure food safety along the food production chain. The key highlight is that research in bioremediation studies should be intensified so that it covers a broad spectrum of contaminants such as heavy metals, pesticides, fertilizers, antibiotics, and microbial contaminants. As such, it should also consider the remediation of biological contaminants at the points of food production, processing, and supply chain.

8.11. References

Adrio, J. L. and Demain, A. L. (2014) ‘Microbial enzymes: tools for biotechnological processes’, *Biomolecules*, 4(1), pp. 117–139. doi: 10.3390/biom4010117.

Ahmad, S. *et al.* (2019) ‘Risk Management of Chemical Hazards Arising During Food Manufacturing’, in *Health and Safety Aspects of Food Processing Technologies*, pp. 403–418. doi: 10.1007/978-3-030-24903-8_13.

Alverez, P. and Illman, W. (2005) ‘Bioremediation technologies’, in Alverez, P. and Illman, W. (eds) *Bioremediation and natural attenuation: Process fundamentals and mathematical models*. John Wiley & Sons, Inc, pp. 351–455. doi: 10.1002/047173862X.

Amin, T. (2018) ‘Application of Biotechnology in Food Plant Waste Utilization’, *International Journal of Advances in Science Engineering and Technology*, 6(3), pp. 33–36.

Araújo, H. W. C. *et al.* (2019) 'Sustainable biosurfactant produced by Serratia marcescens UCP 1549 and its suitability for agricultural and marine bioremediation applications', *Microbial Cell Factories*, 18(1), pp. 1–13. doi: 10.1186/s12934-018-1046-0.

Arora, N. K. (2018) 'Bioremediation: a green approach for restoration of polluted ecosystems', *Environmental Sustainability*, 1(4), pp. 305–307. doi: 10.1007/s42398-018-00036-y.

Azubuike, C. C., Chikere, C. B. and Okpokwasili, G. C. (2016) 'Bioremediation techniques–classification based on site of application: principles, advantages, limitations and prospects', *World Journal of Microbiology and Biotechnology*, 32(11), pp. 1–18. doi: 10.1007/s11274-016-2137-x.

Baez-Rogelio, A. *et al.* (2017) 'Next generation of microbial inoculants for agriculture and bioremediation', *Microbial Biotechnology*, 10(1), pp. 19–21. doi: 10.1111/1751-7915.12448.

Bari, M. L. and Yeasmin, S. (2018) 'Foodborne Diseases and Responsible Agents', in Grumezescu, A. M. and Alina Maria, H. (eds) *Food Safety and Preservation*. Elsevier Inc., pp. 195–229. doi: 10.1016/b978-0-12-814956-0.00008-1.

Bhat, J. A. *et al.* (2019) 'Role of silicon in mitigation of heavy metal stresses in crop plants', *Plants*, 8(3), pp. 1–20. doi: 10.3390/plants8030071.

Bhat, S. A. *et al.* (2018) 'Bioremediation and detoxification of industrial wastes by earthworms: Vermicompost as powerful crop nutrient in sustainable agriculture', *Bioresource Technology*, 252, pp. 172–179. doi: 10.1016/j.biortech.2018.01.003.

Boopathy, R. (2000) 'Factors limiting bioremediation technologies', *Bioresource Technology*, 74(1), pp. 63–67. doi: 10.1016/S0960-8524(99)00144-3.

Cabañas-Vargas, D. D. *et al.* (2013) 'Composting used as a low cost method for pathogen elimination in sewage sludge in Mérida, Mexico', *Sustainability (Switzerland)*, 5(7), pp. 3150–3158. doi: 10.3390/su5073150.

Cecconet, D. *et al.* (2019) 'Controlled sequential biocathodic denitrification for contaminated groundwater bioremediation', *Science of the Total Environment*, 651, pp. 3107–3116.

doi: 10.1016/j.scitotenv.2018.10.196.

Chen, J. *et al.* (2017) 'Potential applications of biosurfactant rhamnolipids in agriculture and biomedicine', *Applied Microbiology and Biotechnology*, 101(23–24), pp. 8309–8319. doi: 10.1007/s00253-017-8554-4.

Chiacchierini, E., Restuccia, D. and Vinci, G. (2004) 'Bioremediation of food industry effluents: Recent applications of free and immobilised polyphenoloxidases', *Food Science and Technology International*, 10(6), pp. 373–382. doi: 10.1177/1082013204049388.

Christou, A. *et al.* (2017) 'The potential implications of reclaimed wastewater reuse for irrigation on the agricultural environment: The knowns and unknowns of the fate of antibiotics and antibiotic resistant bacteria and resistance genes – A review', *Water Research*, 123, pp. 448–467. doi: 10.1016/j.watres.2017.07.004.

Cycoń, M., Mrozik, A. and Piotrowska-Seget, Z. (2019) 'Antibiotics in the soil environment – degradation and their impact on microbial activity and diversity', *Frontiers in Microbiology*, 10(MAR). doi: 10.3389/fmicb.2019.00338.

Dangi, A. K. *et al.* (2019) 'Bioremediation through microbes: systems biology and metabolic engineering approach', *Critical Reviews in Biotechnology*, 39(1), pp. 79–98. doi: 10.1080/07388551.2018.1500997.

Da Silva, I. G. S. *et al.* (2020) 'Soil bioremediation: Overview of technologies and trends', *Energies*, 13(18). doi: 10.3390/en13184664.

Deb, P. (2018) *Environmental Pollution and the burden of Food-Borne Diseases*, *Foodborne Diseases*. Edited by M. A. Holban and A. M. Grumezescu. Elsevier Inc. doi: 10.1016/B978-0-12-811444-5/00014-2.

Devleesschauwer, B. *et al.* (2018) 'Food Safety Economics', in Roberts, T. (ed.) *Food Safety Economics*. Springer, Cham, pp. 107–122. doi: 10.1007/978-3-319-92138-9.

Dotaniya, M. L. *et al.* (2018) 'Bioremediation of metal contaminated soil for sustainable crop production', in Meena, V. (ed.) *Role of Rhizospheric Microbes in Soil*. Singapore: Springer Nature Singapore, pp. 143–165. doi: 10.1007/978-981-10-8402-7.

Drakontis, C. E. and Amin, S. (2020) 'Biosurfactants: Formulations, properties, and applications', *Current Opinion in Colloid and Interface Science*, 48, pp. 77–90. doi: 10.1016/j.cocis.2020.03.013.

Favas. J. C. P. *et al.* (2014) 'Phytoremediation of Soils Contaminated with Metals and Metalloids at Mining Areas: Potential of Native Flora', *Environmental Risk Assessment of Soil Contamination*, (3). doi: 10.5772/57469.

Filazi, A. *et al.* (2017) 'Chemical Contaminants in Poultry Meat and Products', in Manafi, M. (ed.) *Poultry Science*. Intech, pp. 171–190. doi: 10.5772/64893.

Frankenberger, W. T. and Losi, M. E. (2015) 'Applications of Bioremediation in the Cleanup of Heavy Metals and Metalloids', in Turco, H. and R. F. S. (eds) *Bioremediation: Science and application*, pp. 173–210. doi: 10.2136/sssaspecpub43.c11.

Galié, S. *et al.* (2018) 'Biofilms in the food industry: Health aspects and control methods', *Frontiers in Microbiology*, 9(MAY), pp. 1–18. doi: 10.3389/fmicb.2018.00898.

Gaur, N., Narasimhulu, K. and PydiSetty, Y. (2018) 'Recent advances in the bio-remediation of persistent organic pollutants and its effect on environment', *Journal of Cleaner Production*, 198, pp. 1602–1631. doi: 10.1016/j.jclepro.2018.07.076.

Govarthanan, M. *et al.* (2016) 'Bioremediation of heavy metals using an endophytic bacterium Paenibacillus sp. RM isolated from the roots of Tridax procumbens', *Biotech*, 6(2), pp. 1–7. doi: 10.1007/s13205-016-0560-1.

Gupta, S., Pandey, R. A. and Pawar, S. B. (2016) 'Microalgal bioremediation of food-processing industrial wastewater under mixotrophic conditions: Kinetics and scale-up approach', *Frontiers of Chemical Science and Engineering*, 10(4), pp. 499–508. doi: 10.1007/s11705-016-1602-2.

Hazen, T. C. and Stahl, D. A. (2006) 'Using the stress response to monitor process control: pathways to more effective bioremediation', *Current Opinion in Biotechnology*, 17(3), pp. 285–290. doi: 10.1016/j.copbio.2006.03.004.

Hou, D. *et al.* (2020) 'Metal contamination and bioremediation of agricultural soils for food safety and sustainability', *Nature Reviews Earth & Environment*. doi:

10.1038/s43017-020-0061-y.

Hou, D. and Al-Tabbaa, A. (2014) ‘Sustainability: A new imperative in contaminated land remediation’, *Environmental Science and Policy*, 39, pp. 25–34. doi: 10.1016/j.envsci.2014.02.003.

Hu, Y. and Cheng, H. (2016) ‘Health risk from veterinary antimicrobial use in China’s food animal production and its reduction’, *Environmental Pollution*, 219, pp. 993–997. doi: 10.1016/j.envpol.2016.04.099.

Kaczorek, E. *et al.* (2018) ‘The Impact of Biosurfactants on Microbial Cell Properties Leading to Hydrocarbon Bioavailability Increase’, *Colloids and Interfaces*, 2(3), p. 35. doi: 10.3390/colloids2030035.

Kang, D. H. *et al.* (2013) ‘Antibiotic uptake by vegetable crops from manure-applied soils’, *Journal of Agricultural and Food Chemistry*, 61(42), pp. 9992–10001. doi: 10.1021/jf404045m.

Kapahi, M. and Sachdeva, S. (2019) ‘Bioremediation options for heavy metal pollution’, *Journal of Health and Pollution*, 9(24). doi: 10.5696/2156-9614-9.24.191203.

Karigar, C. S. and Rao, S. S. (2011) ‘Role of microbial enzymes in the bioremediation of pollutants: A review’, *Enzyme Research*, 2011(1). doi: 10.4061/2011/805187.

Kaushal, J. *et al.* (2018) ‘Catalase enzyme: Application in bioremediation and food industry’, *Biocatalysis and Agricultural Biotechnology*, 16(August), pp. 192–199. doi: 10.1016/j.bcab.2018.07.035.

Khalid, S. *et al.* (2018) ‘A review of environmental contamination and health risk assessment of wastewater use for crop irrigation with a focus on low and high-income countries’, *International Journal of Environmental Research and Public Health*, 15(5), pp. 1–36. doi: 10.3390/ijerph15050895.

Kosaric, N. (2001) ‘Biosurfactants and Their Application for Soil Bioremediation’, *Food Technology and Biotechnology*, 39(4), pp. 295–304.

Kraemer, S. A., Ramachandran, A. and Perron, G. G. (2019) ‘Antibiotic pollution in the environment: From microbial ecology to public policy’, *Microorganisms*, 7(6), pp. 1–

24. doi: 10.3390/microorganisms7060180.

Krzeminski, P. *et al.* (2019) 'Performance of secondary wastewater treatment methods for the removal of contaminants of emerging concern implicated in crop uptake and antibiotic resistance spread: A review', *Science of the Total Environment*, 648, pp. 1052–1081. doi: 10.1016/j.scitotenv.2018.08.130.

Kumar, M. *et al.* (2019) 'Antibiotics bioremediation: Perspectives on its ecotoxicity and resistance', *Environment International*, 124, pp. 448–461. doi: 10.1016/j.envint.2018.12.065.

Kumar, S. *et al.* (2019) 'Hazardous heavy metals contamination of vegetables and food chain: Role of sustainable remediation approaches - A review', *Environmental Research*, 179, p. 108792. doi: 10.1016/j.envres.2019.108792.

Ławniczak, Ł. *et al.* (2020) 'Microbial degradation of hydrocarbons—basic principles for bioremediation: A review', *Molecules*, 25(4), pp. 1–19. doi: 10.3390/molecules25040856.

Leung, M. (2004) 'Bioremediation: techniques for cleaning up a mess', *Journal of Biotechnology*, 2, pp. 18–22.

Li, Z., Wang, W. and Zhu, L. (2019) 'Effects of mixed surfactants on the bioaccumulation of polycyclic aromatic hydrocarbons (PAHs) in crops and the bioremediation of contaminated farmlands', *Science of the Total Environment*, 646, pp. 1211–1218. doi: 10.1016/j.scitotenv.2018.07.349.

Loughlin, W. A. (2000) 'Biotransformations in organic synthesis', *Bioresource Technology*, 74(1), pp. 49–62. doi: 10.1016/S0960-8524(99)00145-5.

Lu, Y. *et al.* (2015) 'Impacts of soil and water pollution on food safety and health risks in China', *Environment International*, 77, pp. 5–15. doi: 10.1016/j.envint.2014.12.010.

Ma, J. *et al.* (2018) 'Remediation of Arsenic contaminated soil using malposed intercropping of *Pteris vittata L.* and maize', *Chemosphere*, 194, pp. 737–744. doi: 10.1016/j.chemosphere.2017.11.135.

Ma, Y. *et al.* (2018) 'Remediating potentially toxic metal and organic co-contamination of soil by combining in situ solidification/stabilization and chemical oxidation: Efficacy, mechanism, and evaluation', *International Journal of Environmental Research and Public Health*, 15(11), pp. 1–19. doi: 10.3390/ijerph15112595.

Maikudi Usman, M. *et al.* (2016) 'Application of biosurfactants in environmental biotechnology; remediation of oil and heavy metal', *AIMS Bioengineering*, 3(3), pp. 289–304. doi: 10.3934/bioeng.2016.3.289.

Massoud, R. *et al.* (2019) 'Bioremediation of heavy metals in food industry: Application of Saccharomyces cerevisiae', *Electronic Journal of Biotechnology*, 37, pp. 56–60. doi: 10.1016/j.ejbt.2018.11.003.

Mata-Alvarez, J., Macé, S. and Llabrés, P. (2000) 'Anaerobic digestion of organic solid wastes. An overview of research achievements and perspectives', *Bioresource Technology*, 74(1), pp. 3–16. doi: 10.1016/S0960-8524(00)00023-7.

Mu, T. *et al.* (2019) 'Geographical variation in arsenic, cadmium, and lead of soils and rice in the major rice producing regions of China', *Science of the Total Environment*, 677, pp. 373–381. doi: 10.1016/j.scitotenv.2019.04.337.

Naughton, P. J. *et al.* (2019) 'Microbial biosurfactants: current trends and applications in agricultural and biomedical industries', *Journal of Applied Microbiology*, 127(1), pp. 12–28. doi: 10.1111/jam.14243.

Negi, P., Mor, S. and Ravindra, K. (2020) 'Impact of landfill leachate on the groundwater quality in three cities of North India and health risk assessment', *Environment, Development and Sustainability*, 22(2), pp. 1455–1474. doi: 10.1007/s10668-018-0257-1.

Nitschke, M. and Costa, S. G. V. A. O. (2007) 'Biosurfactants in food industry', *Trends in Food Science and Technology*, 18(5), pp. 252–259. doi: 10.1016/j.tifs.2007.01.002.

Odukoya, J., Lambert, R. and Sakrabani, R. (2019a) 'Impact of Crude Oil on Yield and Phytochemical Composition of Selected Green Leafy Vegetables', *International Journal of Vegetable Science*, 25(6), pp. 554–570. doi: 10.1080/19315260.2018.1563845.

Odukoya, J., Lambert, R. and Sakrabani, R. (2019b) ‘Understanding the impacts of crude oil and its induced abiotic stresses on agrifood production: A review’, *Horticulturae*, 5(2), pp. 1–27. doi: 10.3390/horticulturae5020047.

Okocha, R. C., Olatoye, I. O. and Adedeji, O. B. (2018) ‘Food safety impacts of antimicrobial use and their residues in aquaculture’, *Public Health Reviews*, 39(1), pp. 1–22. doi: 10.1186/s40985-018-0099-2.

Olasanmi, I. O. and Thring, R. W. (2018) ‘The role of biosurfactants in the continued drive for environmental sustainability’, *Sustainability (Switzerland)*, 10(12), pp. 1–12. doi: 10.3390/su10124817.

Othmer, K. (2019) ‘Bioremediation’, in *Encyclopedia of chemical technology*, pp. 1–31. doi: 10.1002/0471238961.0209151816180914.a01.pub3.

Pandey, A. *et al.* (2018) ‘Nature based solutions for contaminated land remediation and brownfield redevelopment in cities: A review’, *Bioresource Technology*, 74(1), pp. 1–13. doi: 10.1016/j.biortech.2018.01.003.

Pandey, A. *et al.* (2000) ‘Biotechnological potential of agro-industrial residues. I: Sugarcane bagasse’, *Bioresource Technology*, 74(1), pp. 69–80. doi: 10.1016/S0960-8524(99)00142-X.

Pratush, A., Kumar, A. and Hu, Z. (2018) ‘Adverse effect of heavy metals (As, Pb, Hg, and Cr) on health and their bioremediation strategies: a review’, *International Microbiology*, 21(3), pp. 97–106. doi: 10.1007/s10123-018-0012-3.

Rai, P. K. *et al.* (2019) ‘Heavy metals in food crops: Health risks, fate, mechanisms, and management’, *Environment International*, 125(November 2018), pp. 365–385. doi: 10.1016/j.envint.2019.01.067.

Rehman, K. *et al.* (2018) ‘Prevalence of exposure of heavy metals and their impact on health consequences’, *Journal of Cellular Biochemistry*, 119(1), pp. 157–184. doi: 10.1002/jcb.26234.

Rizwan, M. *et al.* (2016) ‘Cadmium minimization in wheat: A critical review’, *Ecotoxicology and Environmental Safety*, 130, pp. 43–53. doi: 10.1016/j.ecoenv.2016.04.001.

Sarubbo, L. A. *et al.* (2015) ‘Some aspects of heavy metals contamination remediation and role of biosurfactants’, *Chemistry and Ecology*, 31(8), pp. 707–723. doi: 10.1080/02757540.2015.1095293.

Senthil Kumar, P., Femina Carolin, C. and Varjani, S. J. (2018) ‘Pesticides Bioremediation’, in Varjani, S. J. (ed.) *Bioremediation: Applications for Environmental Protection and Management, Energy, Environment, and Sustainability*. Singapore: Springer Nature Singapore, pp. 197–222. doi: 10.1007/978-981-10-7485-1_10.

Sher, S. and Rehman, A. (2019) ‘Use of heavy metals resistant bacteria—a strategy for arsenic bioremediation’, *Applied Microbiology and Biotechnology*, 103(15), pp. 6007–6021. doi: 10.1007/s00253-019-09933-6.

Simões, M., Simões, L. C. and Vieira, M. J. (2010) ‘A review of current and emergent biofilm control strategies’, *LWT - Food Science and Technology*, 43(4), pp. 573–583. doi: 10.1016/j.lwt.2009.12.008.

Singh, R., Glick, B. R. and Rathore, D. (2018) ‘Biosurfactants as a Biological Tool to Increase Micronutrient Availability in Soil: A Review’, *Pedosphere*, 28(2), pp. 170–189. doi: 10.1016/S1002-0160(18)60018-9.

Sivagami, K. *et al.* (2020) ‘Antibiotic usage, residues and resistance genes from food animals to human and environment: An Indian scenario’, *Journal of Environmental Chemical Engineering*, 8(1), p. 102221. doi: 10.1016/j.jece.2018.02.029.

Song, Y. *et al.* (2019) ‘Nature based solutions for contaminated land remediation and brownfield redevelopment in cities: A review’, *Science of the Total Environment*, 663, pp. 568–579. doi: 10.1016/j.scitotenv.2019.01.347.

Spina, F. *et al.* (2018) ‘Fungi as a toolbox for sustainable bioremediation of pesticides in soil and water’, *Plant Biosystems*, 152(3), pp. 474–488. doi: 10.1080/11263504.2018.1445130.

Sutherland, D. L. and Ralph, P. J. (2019) ‘Microalgal bioremediation of emerging contaminants - Opportunities and challenges’, *Water Research*, 164, p. 114921. doi: 10.1016/j.watres.2019.114921.

Thijs, S. *et al.* (2016) ‘Towards an enhanced understanding of plant-microbiome interactions to improve phytoremediation: Engineering the metaorganism’, *Frontiers in Microbiology*, 7, pp. 1–15. doi: 10.3389/fmicb.2016.00341.

Thompson, L. A. and Darwish, W. S. (2019) ‘Environmental Chemical Contaminants in Food: Review of a Global Problem’, *Journal of Toxicology*. pp. 1–14. doi: 10.1155/2019/2345283.

Villarroel Hipp, M. P. and Silva Rodríguez, D. (2018) ‘Bioremediation of piggery slaughterhouse wastewater using the marine protist, Thraustochytrium kinney VAL-B1’, *Journal of Advanced Research*, 12, pp. 21–26. doi: 10.1016/j.jare.2018.01.010.

Wang, J., Chu, M. and Ma, Y. (2018) ‘Measuring rice farmer’s pesticide overuse practice and the determinants: A statistical analysis based on data collected in Jiangsu and Anhui provinces of China’, *Sustainability (Switzerland)*, 10(3), pp. 1–17. doi: 10.3390/su10030677.

Wang, P. *et al.* (2019) ‘Cadmium contamination in agricultural soils of China and the impact on food safety’, *Environmental Pollution*, 249, pp. 1038–1048. doi: 10.1016/j.envpol.2019.03.063.

Weber, R. *et al.* (2019) ‘Assessment of pops contaminated sites and the need for stringent soil standards for food safety for the protection of human health’, *Environmental Pollution*, 249(May), pp. 703–715. doi: 10.1016/j.envpol.2019.03.066.

Whelan, M. J. *et al.* (2015) ‘Fate and transport of petroleum hydrocarbons in engineered biopiles in polar regions’, *Chemosphere*, 131, pp. 232–240. doi: 10.1016/j.chemosphere.2014.10.088.

Yang, B. *et al.* (2020) ‘Journal Pre-proof’, *Food Control*. doi: 10.1016/j.foodcont.2020.107372.

Zhang, X. *et al.* (2015) ‘Impact of soil heavy metal pollution on food safety in China’, *PLoS ONE*, 10(8), pp. 1–14. doi: 10.1371/journal.pone.0135182.

CHAPTER 9: COMPLIANCE SAMPLING AND MONITORING OF HEAVY METAL ACCUMULATION IN SELECTED VEGETABLES USING ICP-OES: A PROBABILISTIC HUMAN HEALTH RISK ASSESSMENT

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Abstract

The contamination of vegetables by heavy metals is a public health concern. The contamination in most agricultural holdings is due to polluted environments. Vegetables are not just a delicacy but an integral part of human diets globally. Human exposure to heavy metals was analysed using the Inductively Coupled Plasma Optical Emissions Spectrometry (ICP-OES) technique. Moreover, probabilistic human health-risk assessments (carcinogenic and non-carcinogenic risks) were conducted for adults and children. In this study, 6 vegetable types were selected from the Bloemfontein Fresh Produce Market in South Africa and tested for the presence of arsenic (As), copper (Cu), lead (Pb) and cadmium (Cd). The results show that the mean concentration of Cd in Spinach, Onion and cabbage exceeds the maximum allowable limit for metals in foodstuffs as per the *Codex Alimentarius*. However, for non-carcinogenic human health effects through the ingestion exposure pathway, none of the trace metals has a hazard quotient ≥ 1 thus, showing the unlikelihood of adverse health effects. The Target Hazard Quotient (THQ) in order of exposure for all vegetable types was ranked as follows: As > Cd > Cu > Pb. The low hazard quotient may be attributed to good agricultural practices, i.e., location away from heavy industries and polluted land, the use of treated water and environmentally friendly fertilizers, and pesticides in the food production chain. Precautionary steps must be adhered to by local farmers at fresh-produce markets to prevent contamination of food sources in the food production chain.

Keywords: Risk assessments, human health, food safety, heavy metals, target hazard quotient, ICP-OEL

9.1. Introduction

South Africa is one of the countries that subscribe to the WHO standards regarding the control of trace metals in foods. Therefore, the country has set regulatory limits for a variety of foodstuffs from meat and meat products to vegetables, fruits and legumes. Food is the source of vital nutrients such as carbohydrates, vitamins and minerals, which are fundamental to the human body (Nuapia, Chimuka and Cukrowska, 2018). Moreover, the World Health Organization recommends five portions of fruits and vegetables daily, excluding those rich in starch, due to their health benefits in reducing cancer and cardiovascular mortality (Okop *et al.*, 2019; Oliveri Conti *et al.*, 2020). However, heavy-metal contamination of vegetables is reported to negatively impact their protein, fat and carbohydrate content (Ali and Khan, 2019).

Certain crops are known to have the ability to retain trace elements from contaminated soil and water (Firth *et al.*, 2019; Mehri *et al.*, 2021). Carcinogenic and non-carcinogenic effects of metals in vegetables contaminated through the soils are a major health risk, more so when the contamination emanated from the soil polluted with wastewater (Ali and Khan, 2019). Anthropogenic activities such as mining operations and other atmospheric pollution-emitting industries have been reported to cause significant pollution, which is ultimately absorbed by the food plants (Proietti, Frazzoli and Mantovani, 2015; Ripanda *et al.*, 2022; Zulkafflee *et al.*, 2022). Furthermore, the usage of low-quality fertilizers can be the reason for the increased heavy-metal concentration such as cadmium in the soil (Loi *et al.*, 2018). This ultimately becomes a food safety issue due to the concentration of toxic metals in the food chain. There is a need to monitor the contents of elements in food to ensure the quality and safety of the food products (Marguí *et al.*, 2021). Research shows that trace elements such as Cu, Zn, Mn, and Fe form an essential part of the human diet with a variety of benefits, namely metabolism (De Aragão Tannus *et al.*, 2021), biosynthesis and antioxidant processes (Marguí *et al.*, 2021). However, researchers also caution that these elements, in high concentrations, are potentially toxic (Marguí *et al.*, 2021; De Aragão Tannus *et al.*, 2021). Consequently, these can disrupt the biochemical processes causing liver, kidney, bone, spleen and brain complications (Fathabad *et al.*, 2018; Nuapia *et al.*, 2018).

The awareness of food safety concerns over toxic heavy metals has led to stringent measures placed in the food industry, especially through regulatory authorities to determine the chemical content in food through allowable limits and threshold standards. Therefore, the development of fast, simple, and sensitive methods of detecting these contaminants is of special interest to food regulators and consumers (Bressy *et al.*, 2013; Park *et al.*, 2019; Marguí *et al.*, 2021). Inductively coupled plasma optical-emission spectrometry (ICP-OES) is one of the commonly used techniques for quantitative elemental analysis of plant samples (Habte *et al.*, 2016; Marguí *et al.*, 2021). Other techniques include inductively coupled plasma-mass spectrometry (ICP-MS) (De Aragão Tannus *et al.*, 2021), flame atomic-absorption spectrometry (F AAS) and electrothermal atomic-absorption spectrometry (ET-AAS) (Bressy *et al.*, 2013).

This research aimed to evaluate the trace-metal contamination levels of five groups of vegetables sold within the Bloemfontein region in the Free State Province, South Africa. The objective was to measure the heavy-metal concentration of the selected vegetables against the maximum allowable limits for heavy metals in vegetables as per the *Codex Alimentarius*. Moreover, risk assessments for adults based on the hazard quotient and the estimated daily intake were conducted. This will assist in creating a base-line-baseline understanding of the typical exposure levels from vegetables bought from informal street vendors and the more formal big retail supermarkets.

9.2. Material and methods

9.2.1. Sample collection

The food consumption studies conducted in South Africa listed maize meal and bread as the most consumed foods by 78% of the population (Schönfeldt, Gibson and Vermeulen, 2010; De Cock *et al.*, 2013). However, in this study, vegetables that were analysed are a representation and a significant part of the South African diet (McHiza *et al.*, 2015). A total of 18 vegetable samples were randomly selected at the Bloemfontein fresh-produce markets (29°06'49"S 26°15'48"E) as shown in Figure 9.1. Bloemfontein is one of the major cities located in the Free State Province of South Africa. All samples were stored in their original packaging and closed plastic containers upon collection.

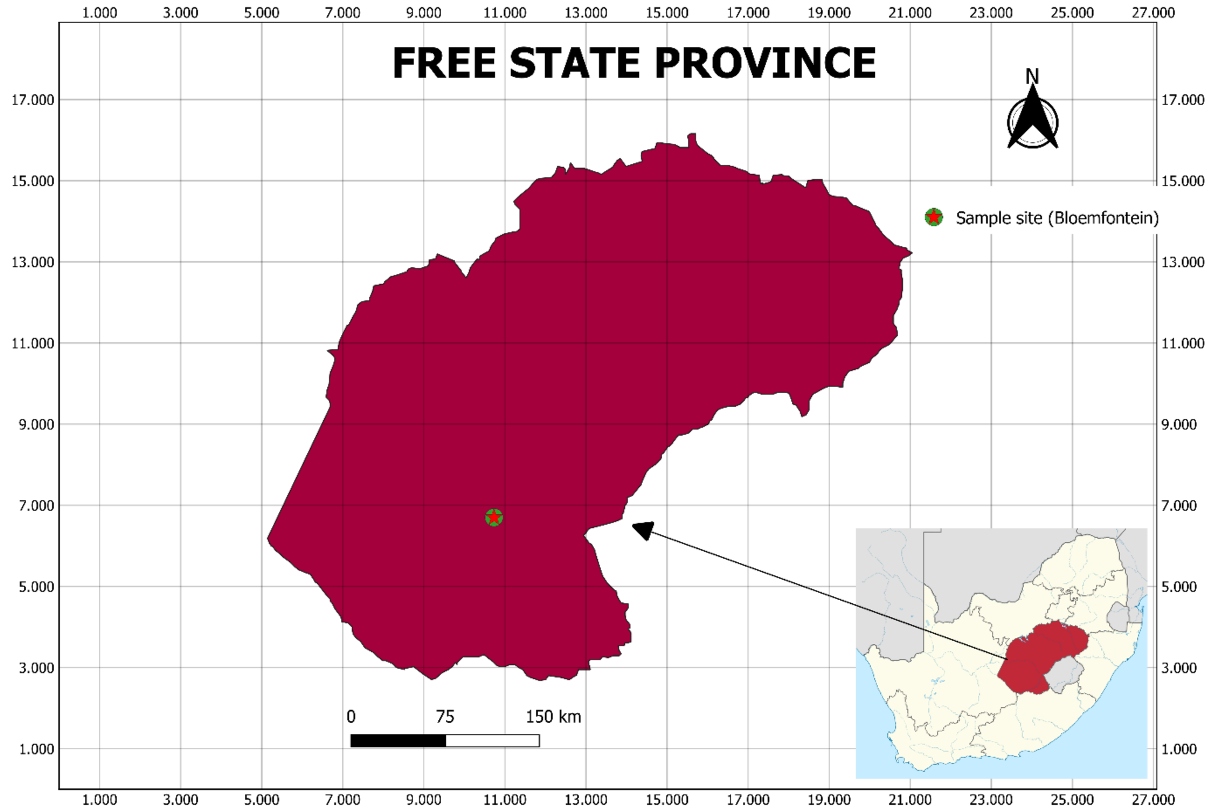

Figure 9.1: Study area, Bloemfontein in the Mangaung Metropolitan Municipality, South Africa**.**

9.3. Experiment procedure

9.3.1. Chemicals and reagents

The chemicals (nitric acid [HNO_3], hydrogen peroxide [H_2O_2]) used for trace element analysis and deionized water were of analytical grade.

9.3.2. Sample preparation

Vegetable samples were purchased from local food markets, transferred to the laboratory, and stored in plastic Ziploc bags in a refrigerator at 4° C. The samples were rinsed thoroughly under running tap water, followed by ultrapure de-ionised water to remove contaminants and dust particles that could adhere to surfaces (Gupta *et al.*, 2018). The purpose is to determine m heavy metals contamination within the vegetables, not the surface. The samples included spinach, beetroot, carrots, onion, tomato, and cabbage (Table 9.1). All samples were peeled and chopped into small cubes and dried in an oven for 24h at a temperature of 60° Celsius. Dried vegetables were ground with a titanium blade-blender to a smooth and homogenized product, then sieved using a standard laboratory sieve to remove bigger particles (Figure 2 shows ground vegetables observed through a scanning electron microscope). For each vegetable, pellets were divided into triplicates.

Table 9.1: List of vegetables analysed.

Sample	Vegetable	Genus's specie
A	Spinach	*Spinacia oleracea*
B	Beetroot	*Beta vulgaris*
C	Carrot	*Daucus carota*
D	Onion	*Allium cepa*
E	Cabbage	*Brassica oleracea*
F	Tomato	*Solanum lycopersicum*

9.3.3. Digestion procedure and ICP-OES analysis

The concentration of 8 trace elements (As, Cd, Cu, Fe, Mn, Ni, Pb, Zn) was analysed in each sample. An open-vessel acid-digestion method was used to digest each sample. About 0.5 g of each sample was weighed and mixed with 10 ml of 65% nitric acid (HNO_3) and 3 ml of hydrogen peroxide 35% (H_2O_2) in a polypropylene centrifuge tube. Each sample was closed to prevent the contamination and loss of analytes; however, a small hole was left open to release the oxygen from the reaction of hydrogen peroxide. The mixtures were left at room temperature for 24 hours as part of pre-digestion. A near-transparent mixture was observed in most samples after 24 hours. Each mixture was transferred to a volumetric flask and heated on a hot plate for 15 minutes at 180 °C under a fume hood until the hydrogen gas had escaped and the digestion process was completed. After heating, the digested sample solutions were cooled at room temperature and then brought to 50 ml volume with ultrapure, de-ionised water. The solution was filtered using a Nalgene filtration system with throttle bottles and a 0.2µm pore size nitrate membrane filter. Then the filtrate was transferred to a 50 ml polypropylene tube washed with ultrapure de-ionised water. For each prepared sample, the same method was applied to prepare the blank solutions. All analyses of vegetable samples were performed using the Plasma Atomic Emissions Spectrometer (Shimadzu, Model ICPE9820 made in Japan). The instrument's parameters are shown in Table 9.2.

Table 9.2: Instrument parameters for ICP OES.

ICP-OES	Power (kW)	1.21
	Plasma Argon flow rate (L/min)	14.00
	Auxiliary Argon flow rate	1.20
	Nebulizer Argon flow rate	0.70
	OCD temperature (C)	-14.99
	Pump rate (rpm)	0
	Direction	Axial

9.4. Data analysis

The Statistical Package for Social Sciences (SPSS version 27, IBM, New York, United States of America) was used to perform statistical analysis in this study. The analysis's measures of central tendency statistics are the mean, range and standard deviation. Further analysis included a one-way analysis of variance (ANOVA) to determine significant differences and the Shapiro-Wilk test to ascertain if the samples are from a normal distribution.

9.5. Health risk assessment

In this study, the potential effects of heavy metal exposure from the selected vegetables were predicted using the estimated daily intake (EDI) and the target hazard quotient (THQ). The United States Environmental Protection Agency (EPA) describes the Hazard Quotient (HQ) and Hazard Index (HI) as approaches for risk characterisation of single chemicals and mixtures in various scenarios, respectively. The HQ is the ratio of exposure concerning a predetermined reference dose (Goumenou and Tsatsakis, 2019). According to Lebelo *et al.* (2021), estimated daily intake represents the average ingested dose. The THQ is used to calculate the non-carcinogenic risk of heavy metals (Doabi *et al.*, 2018; Fathabad *et al.*, 2018) as denoted in the equation below.

$$THQ = \frac{\text{CDI}}{RfD} \tag{1}$$

Chronic daily intake is recorded as the estimated amount of ingested heavy metals per kilogram of body weight. The RfD is the oral reference dose of metals, which is measured in milligrams per kilogram per day (mg/kg.d) when ingested. The EPA has indicated the following reference doses for As, Cd, Cu, and Pb as 0.003, 0.0005, 0.04, and 0.0085 mg/kg, respectively (Lizardi *et al.*, 2020).

$$CDI = \frac{\mathrm{C\ x\ IRi\ x\ EFi\ x\ EDi}}{BWi\ X\ AT} \tag{2}$$

C represents the concentration of heavy metals in selected vegetables, which is measured in Mg/kg. The ingestion rate for adults is represented by IRi (0.015 kg/per day) in South Africa (Kucich and Wicht, 2016). EFi symbolises the exposure frequency presented 365 days of the year for both adults and children. EDi is the exposure duration, which is estimated as 70 years for adults. BWi represents body weight for adults, which is estimated as 71.8 kg (U.S. EPA, 2012). The average life span measured in days for adults in adults is denoted as AT(EF x ED), 25 550. A target hazard quotient greater than 1 (HQ ≥1) shows that a potential adverse effect is likely and *vice versa* (Fathabad *et al.*, 2018; Rai *et al.*, 2019; Kharazi *et al.*, 2021).

The total hazard-index estimate signifies the sum of multiple Hazard Quotients. It is assumed that the severity of the adverse effect is positively correlated to the total number of multiple exposures (Gupta *et al.*, 2018; Nuapia, Chimuka and Cukrowska, 2018).

$$HI = \sum \mathrm{THQ} = \mathrm{THQAs} + \mathrm{THQCd} + \mathrm{THQCu} + \mathrm{THQPb} \tag{3}$$

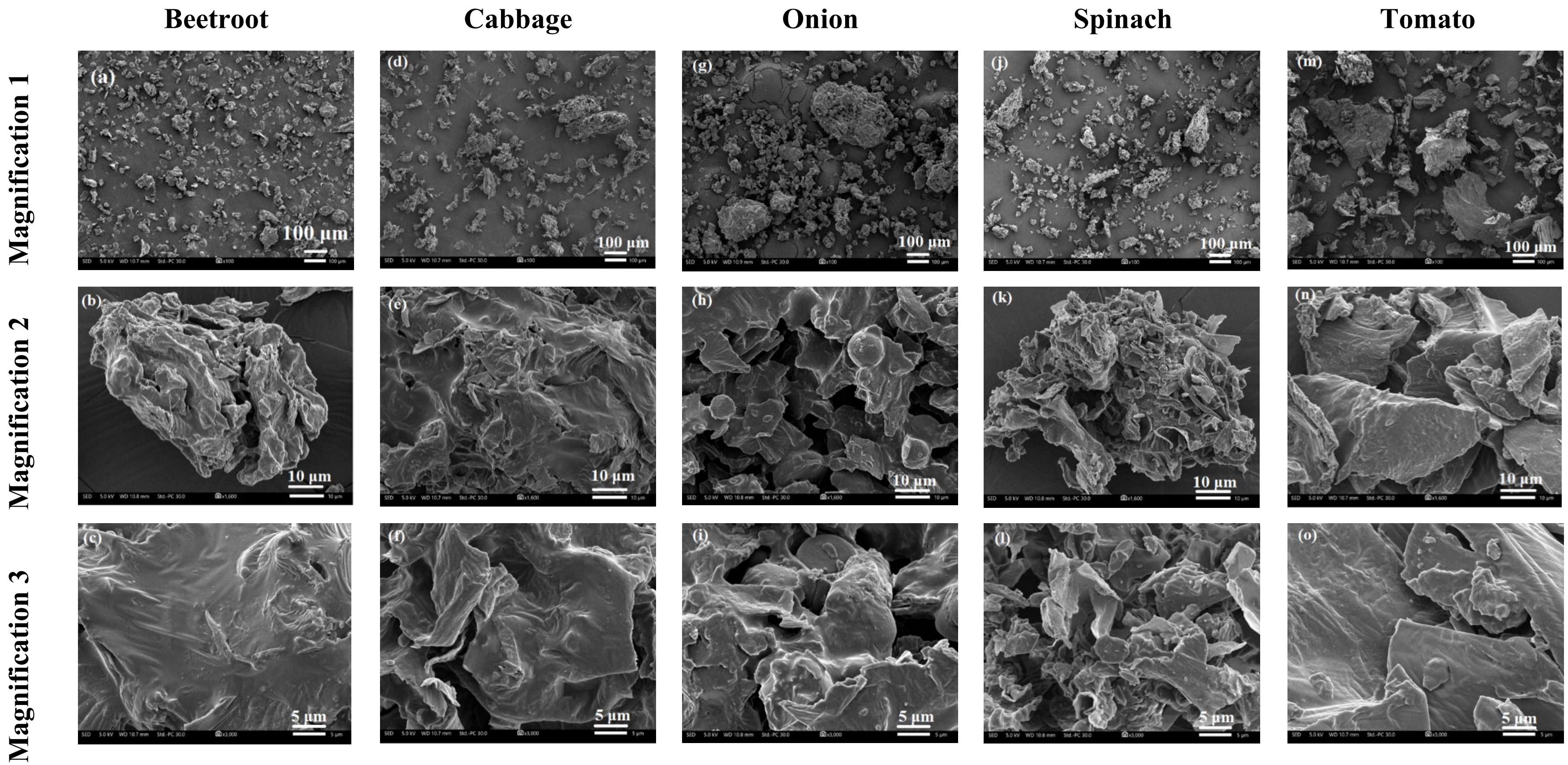

Figure 9.2: SEM-EDS cross-sectional morphology images of vegetables from low to high magnification. Beetroot (a-c), Cabbage (d-f), Onion (g-i), Spinach (j-l), Tomato (m-o).

9.6. Results and discussion

9.6.1. Analysis of variance (ANOVA)

Assumptions were made before the ANOVA analysis could be conducted. Firstly, the observations should be independent. Secondly, the dependent variable should be measured on at least an interval scale. Further, the distributions within groups should be normally distributed. Lastly, the variances in each experimental condition need to be fairly similar (Field, 2015; Sauder and DeMars, 2019). In this study, the first two assumptions were met, and further analysis was done to test for other assumptions. The Shapiro-Wilk test was conducted on each group used in the ANOVA analysis (Table 9.3). If the p-value of the Shapiro-Wilk test is below 0.05, the group sample is not normally distributed.

The results of the Shapiro-Wilk test for each heavy metal used in the ANOVA analysis are shown in Table 9.4. When investigating the p-values of the heavy metal As, Tomato could not be included in the analysis because ANOVA requires three or more samples to be conducted. Further, it can be seen that none of the values is lower than 0.05, indicating that the measurements in each group are normally distributed. Similarly, when investigating Cu and Pb, none had a value lower than 0.05. Therefore, an ANOVA analysis was thereby conducted on the As, Pb and Cu heavy-metal data. The spinach group, when investigating for Cd, had a p-value of lower than 0.05, indicating that the spinach group data are not normally distributed. Therefore, the non-parametric test (Kruskal Wallis test) was performed to compare the means of the six vegetable groups containing Cd (Table 9.5). The averages were constant in the tomato, cabbage and onion groups and have been omitted for the Shapiro-Wilk test for cadmium.

Table 9.3: Descriptive statistics for vegetable groups.

Trace elements		**N**	**Mean**	**Std deviation**	**Standard error**	**95% Confidence Interval for Mean**	
						Lower Bound	**Upper Bound**
As	Spinach	3	.194433	.1241479	.0716768	-.113967	.502834
	Beet	3	.038289	.0198412	.0114553	-.010999	.087577
	Carrot	3	.016767	.0105292	.0060790	-.009389	.042923
	Tomato	2	.010383	.0079903	.0056500	-.061407	.082173
	Cabbage	3	.011956	.0050790	.0029323	-.000661	.024572
	Onion	3	.011722	.0083840	.0048405	-.009105	.032549
	Total	17	.049427	.0830171	.0201346	.006744	.092111
Cu	Spinach	3	.238556	.0266674	.0153964	.172310	.304801
	Beet	3	.288889	.0351352	.0202853	.201608	.376170
	Carrot	3	.243778	.0137005	.0079100	.209744	.277812
	Tomato	3	.316444	.0113741	.0065669	.288190	.344699
	Cabbage	3	.233667	.0167564	.0096743	.192041	.275292
	Onion	3	.222556	.0005092	.0002940	.221291	.223820
	Total	18	.257315	.0387108	.0091242	.238064	.276565
Pb	Spinach	3	.082211	.0746424	.0430948	-.103211	.267633
	Beet	3	.013633	.0004702	.0002715	.012465	.014801
	Carrot	3	.013800	.0009821	.0005670	.011360	.016240
	Tomato	3	.012111	.0014519	.0008383	.008504	.015718
	Cabbage	3	.016878	.0017614	.0010170	.012502	.021253
	Onion	3	.016000	.0006119	.0003533	.014480	.017520
	Total	18	.025772	.0365162	.0086069	.007613	.043931
Cd	Spinach	3	.186444	.1078684	.0622779	-.081516	.454404
	Beet	3	.121556	.0005092	.0002940	.120291	.122820
	Carrot	3	.121333	.0003333	.0001925	.120505	.122161
	Tomato	3	.121000	.0000000	.0000000	.121000	.121000
	Cabbage	3	.122000	.0000000	.0000000	.122000	.122000
	Onion	3	.122000	.0000000	.0000000	.122000	.122000
	Total	18	.132389	.0445853	.0105088	.110217	.154561

Table 9.4: The Shapiro-Wilk test for trace elements.

			Shapiro-Wilk		
	Group	**N**	**Statistic**	**df**	**p-value**
Average **AS**	Spinach	3	.906	3	.406
	Beet	3	.837	3	.206
	Carrot	3	.966	3	.647
	Tomato	2	-	-	-
	Cabbage	3	.797	3	.107
	Onion	3	1.000	3	.976
Average **Cd**	Spinach	3	0.751	3	0.003*
	Beet	3	0.964	3	0.637
	Carrot	3	1	3	1
Average **Cu**	Spinach	3	.777	3	.060
	Beet	3	.992	3	.832
	Carrot	3	.995	3	.866
	Tomato	3	.993	3	.838
	Cabbage	3	.784	3	.076
	Onion	3	.964	3	.637
Average **Pb**	Spinach	3	.783	3	.076
	Beet	3	.985	3	.765
	Carrot	3	.969	3	.661
	Tomato	3	.930	3	.488
	Cabbage	3	.950	3	.569
	Onion	3	.858	3	.261

***= P value <0.05**

The means of the vegetable groups containing Cd are not normally distributed. The non-parametric test, namely the Kruskal Wallis test, compared the means of the six vegetable groups containing Cd, and there was a statistically significant difference between vegetable groups containing the Cd heavy metal, H (5) = 14.98, $p = 0.010$.

Levene's test of homogeneity of variances (Table 9.5) showed a *p*-value below 0.05, meaning that variances of the different groups are not similar and that the assumption of conducting an ANOVA analysis has been violated. After the Welch's test, it can be concluded that there are no differences in the concentration of As between the vegetable groups. For Cu, the *p*-value of Levene's test is above 0.05. Consequently, a one-way ANOVA analysis for the Cu heavy metal was conducted and there was a statistically significant difference between the vegetable groups at a 0.05 significance level ($p = 0.001$), as shown in Table 9.6.

Table 9.5: Levene's and Welch's test for As, Cu, and Pb.

	Tests	Statistic	df1	df2	p-value
As	**Levene's**	8.357	5	11	.002*
	Welch	1.525	5	4.594	.336
Cu	**Levene's**	2.612	5	12	.080
Pb	**Levene's**	15.327	5	12	.000*
	Welch	6.072	5	5.357	.030*

***= P value <0.05**

Table 9.6: ANOVA table for Cu heavy metal.

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.020	5	.004	9.618	.001*
Within Groups	.005	12	.000		
Total	.025	17			

***= P value <0.05**

9.6.2. Human health risk assessment

The concentrations of As, Cu, Pb, and Cd are presented in Table 9.7. The total mean for all the studied heavy metals (except Cd in Spinach, Tomato, Cabbage and Onion) was lower in all vegetables, signifying that they comply with the *Codex Alimentarius* maximum limits for metals in foodstuffs. According to the codex, the maximum level for the Cadmium metal is 0.2 mg/kg, 0.05 mg/kg, and 0.05 mg/kg in Spinach, Cabbage and Onion respectively. Research shows that Cd has several human health effects, the most notable being cancer, kidney damage, testicular dysfunction and infertility (Kiran, Bharti and Sharma, 2021). The sequence means for all the studied vegetables are as follows: Cu>Cd>As>Pb. The highest concentration of Cu reported in this study (0.32 mg/kg) for Tomatoes is lower than the 7.85 in wheat and 4.3 mg/kg reported by Doabi *et al.*, (2018). However, it can be argued that the vegetable types are not comparable, due to factors such as irrigation and geographical area (Adebiyi *et al.*, High concentrations of Cu in a human diet cause renal and metabolic dysfunctions (Rai *et al.*, 2019). In addition, essential elements such as Fe, Ca, An and Mg are vital in the human diet; however, excessive concentration can be detrimental over time. Conditions causing functional morphological changes, such as pneumonia, fever, chest pains, etc., have been documented where such metals are deficient (Rai *et al.*, 2019; Kiran, Bharti and Sharma, 2021).

Table 9.7: Concentration of heavy metals dry weight (mg/kg dry weight) Mean±Std deviation.

Vegetable		**Heavy metals (mg/kg)**			
		Arsenic	**Copper**	**Lead**	**Cadmium**
		As	**Cu**	**Pb**	**Cd**
	Spinach	0.19 ± 0.12	0.24 ± 0.03	0.08 ± 0.07	0.19 ± 0.11*
	Beet	0.04 ± 0.02	0.29 ± 0.04	0.01 ± 0.00	0.12 ± 0.00
	Carrot	0.02 ± 0.01	0.24 ± 0.01	0.01± 0.00	0.12 ± 0.00
	Tomato	0.01 ± 0.01	0.32 ± 0.01	0.01 ± 0.00	0.12 ± 0.00*
	Cabbage	0.01 ± 0.01	0.23 ± 0.02	0.02 ± 0.00	0.12 ± 0.00*
	Onion	0.01 ± 0.01	0.22 ± 0.00	0.02 ± 0.00	0.12 ± 0.00*

*= Exceeding maximum limits as per the *Codex Alimentarius* (Codex, 2009; National Department of Health, 2018)

Findings of non-carcinogenic human health effects through the ingestion exposure pathways are reported in Table 9.8. The results show that none of the heavy metals has a hazard quotient ≥ 1. A hazard quotient greater than one demonstrates the likelihood of risk, as reported in numerous studies. In this study, all vegetables show low hazard quotients, which may be attributed to good agricultural practices, i.e., location away from heavy industries and polluted land, the use of treated water and environmentally friendly fertilizers and pesticides in the food production chain. Moreover, the results could have been influenced by metal extraction techniques and the sensitivity of the ICP-OES; however, it has been proven reliable and sensitive to detect some heavy metals, even at low concentrations.

Despite the hazard quotient values being less than 1, arsenic values in spinach displayed the highest HI whilst lead had the lowest value. Overexposure to arsenic has been reported to cause skin lesions, melanosis, neurologic complications, hematemesis, cardiovascular problems, weakness and weight loss (Rai *et al.*, 2019; Kiran, Bharti and Sharma, 2021). In addition, potential exposure to lead also has adverse effects such as cardiovascular problems, hypertension, anaemia, infertility, miscarriage and kidney problems among the notable health conditions (Doabi *et al.*, 2018; Adebiyi, Ore and Ogunjimi, 2020).

Table 9.8: Estimated Hazard Quotients (HQ) of the analysed trace metals.

Vegetable	**Chronic daily intake (mg/kg)**				**Hazard Quotients**			
	As	**Cu**	**Pb**	**Cd**	**As**	**Cu**	**Pb**	**Cd**
Spinach	0.00004	0.0005	0.00002	0.00004	0.13	0.001	0.002	0.08
Beetroot	0.000008	0.00006	0.000002	0.00003	0.03	0.0015	0.0002	0.06
Carrot	0.000004	0.0005	0.000002	0.00003	0.01	0.001	0.0002	0.06
Tomatoes	0.000002	0.00007	0.000002	0.00003	0.007	0.002	0.0002	0.06
Cabbage	0.000002	0.00005	0.0005	0.00003	0.007	0.001	0.0005	0.06
Onion	0.000002	0.00005	0.0005	0.00003	0.007	0.001	0.0005	0.06

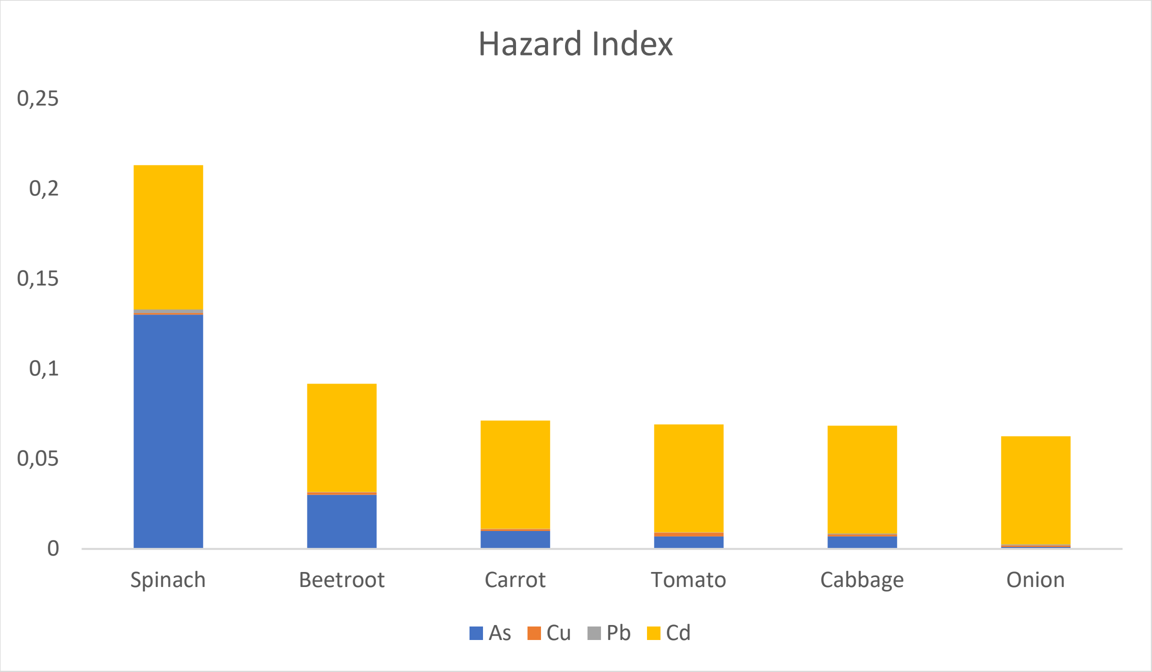

Figure 9.3: Hazard Index (HI) for As, Cu, Pb and Cd.

Essential elements can be perceived as essential poisons because they are potentially toxic at higher concentrations (Tongesayi *et al.*, 2013). Examples of essential elements include Manganese (Mn) and Zinc (Zn). These are elements that are required by living organisms for various physiological and biochemical processes (Ali and Khan, 2019). The overdose of these elements may arise from accidental contamination, or it may be compounded by supplements. There is a challenge in monitoring these elements because attention is usually focused on the non-essential elements. However, if they are consumed beyond the recommended threshold, they may cause adverse health effects (Ali and Khan, 2018). Certain grains and plants have been reported to accumulate the metals at levels several times higher than the soil. Therefore, it is imperative to monitor the concentrations of metals in foodstuffs consumed globally. This is in consideration of international trade in the food industry. As a result, contamination in one corner of the globe may ultimately affect populations on other continents. Research shows that manganese accumulation is mostly found in foodstuffs such as spinach and herbs (Tongesayi *et al.*, 2013). Adverse effects on human health include hallucinations, forgetfulness, impotence in men, bronchitis, etc. However, a manganese deficiency is associated with skin problems, blood clotting, obesity, congenital disabilities, etc. Zinc, on the other hand, causes stomach cramps, vomiting, anaemia and skin irritations when overdosed (Tongesayi *et al.*, 2013).

Heavy metals are major environmental pollutants. They are naturally occurring metals with an atomic number higher than 20. In addition, their elemental density is greater than 5 g cm^{-3} (Ali and Khan, 2019) and are at least five times denser than water (Kiran, Bharti and Sharma, 2021). The long-term consumption of these heavy metals in contaminated crops may result in the disruption of biological processes in humans (Gall, Boyd and Rajakaruna, 2015; Rai *et al.*, 2019). Higher concentrations of Lead (Pb) cause kidney problems, diabetes and hypertension, as reported in patients with blood Pb levels around 7.5 µg dL^{-1}. Most of the contamination of non-essential metals (As, Cr, Ni, Cu, Pb) have been found in cities close to mining, industrial and agricultural activities. The cocktail effect of the major heavy metals (As, Cd, Hg, Pb), which even at low dose exposures have higher toxicity should be monitored (Ali and Khan, 2019; Ali, Khan and Ilahi, 2019; Rai *et al.*, 2019). This study shows that the concentration of the non-essential metals was low to cause adverse health effects.

9.7. Conclusion and recommendations

The consumption of contaminated food can have a detrimental effect on human health. The contamination can be controlled through targeted and routine monitoring of human health risk assessments. This study investigated the concentration and potential human health effects of trace metals in vegetables sold in the Mangaung fresh-produce markets in Bloemfontein, South Africa. The concentration of cadmium in spinach, tomato, cabbage, and onion exceeded the maximum permissible limits set by the *Codex Alimentarius*. However, the estimated daily intake and hazard quotients were less than one. Moreover, the hazard index shows that none of the studied metals (As, Cu, Pb, Cd) had values greater than 1. This demonstrated that there are no anticipated adverse health effects. The Target Hazard Quotient (THQ) in order of exposure for all vegetables was ranked as follows: As > Cd > Cu > Pb. Based on the results of this study, precautions should be taken to control the accumulation of cadmium in spinach and cabbage due to potentially adverse effects. These can be consumed in moderate amounts or in agricultural practices to reduce the accumulation of selected vegetables. Future studies will incorporate more essential and non-essential metals in the analysis. In addition, vegetable samples will be collected directly at the beginning of the food production chain (farms).

Acknowledgements

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9.8. References

Adebiyi, F. M., Ore, O. T. and Ogunjimi, I. O. (2020) 'Evaluation of human health risk assessment of potential toxic metals in commonly consumed crayfish (*Palaemon hastatus*) in Nigeria', *Heliyon*, 6(1), p. e03092. doi: 10.1016/j.heliyon.2019.e03092.

Ali, H. and Khan, E. (2018) 'Bioaccumulation of non-essential hazardous heavy metals and metalloids in freshwater fish. Risk to human health', *Environmental Chemistry Letters*, 16(3), pp. 903–917. doi: 10.1007/s10311-018-0734-7.

Ali, H. and Khan, E. (2019) 'Trophic transfer, bioaccumulation, and biomagnification of non-essential hazardous heavy metals and metalloids in food chains/webs – Concepts and implications for wildlife and human health', *Human and Ecological Risk Assessment*, 25(6), pp. 1353–1376. doi: 10.1080/10807039.2018.1469398.

Ali, H., Khan, E. and Ilahi, I. (2019) 'Environmental chemistry and ecotoxicology of hazardous heavy metals: Environmental persistence, toxicity, and bioaccumulation', *Journal of Chemistry*, 2019(Cd). doi: 10.1155/2019/6730305.

de Aragão Tannus, C. *et al.* (2021) 'Multielement Determination in Medicinal Plants and Herbal Medicines Containing *Cynara scolymus L., Harpagophytum procumbens*

D.C., and *Maytenus ilifolia (Mart.*) ex Reiss from Brazil Using ICP OES', *Biological Trace Element Research*, 199(6), pp. 2330–2341. doi: 10.1007/s12011-020-02334-1.

Bressy, F. C. *et al.* (2013) 'Determination of trace element concentrations in tomato samples at different stages of maturation by ICP OES and ICP-MS following microwave-assisted digestion', *Microchemical Journal*, 109, pp. 145–149. doi: 10.1016/j.microc.2012.03.010.

De Cock, N. *et al.* (2013) 'Food security in rural areas of Limpopo province, South Africa', *Food Security*, 5(2), pp. 269–282. doi: 10.1007/s12571-013-0247-y.

Codex, A. (2009) *CODEX STAN 193-1995 Page 1 of 44*, *Natural Toxins*.

Doabi, S. A. *et al.* (2018) 'Pollution and health risk assessment of heavy metals in agricultural soil, atmospheric dust and major food crops in Kermanshah province, Iran', *Ecotoxicology and Environmental Safety*, 163 (January), pp. 153–164. doi: 10.1016/j.ecoenv.2018.07.057.

Fathabad, A. E. *et al.* (2018) 'Determination of heavy metal content of processed fruit products from Tehran's market using ICP- OES: A risk assessment study', *Food and Chemical Toxicology*, 115 (April), pp. 436–446. doi: 10.1016/j.fct.2018.03.044.

Field, A. (2015) *Discovering statistics using IBM SPSS statistics*. 5th ed, *SAGE edge*. Los Angeles: SAGE.

Firth, D. C. *et al.* (2019) 'Monitoring of trace metal accumulation in two South African farmed mussel species, M*ytilus galloprovincialis* and *Choromytilus meridionalis*', *Marine Pollution Bulletin*, 141 (October 2018), pp. 529–534. doi: 10.1016/j.marpolbul.2019.03.007.

Gall, J. E., Boyd, R. S. and Rajakaruna, N. (2015) 'Transfer of heavy metals through terrestrial food webs: a review', *Environmental Monitoring and Assessment*, 187(4). doi: 10.1007/s10661-015-4436-3.

Goumenou, M. and Tsatsakis, A. (2019) 'Proposing new approaches for the risk characterisation of single chemicals and chemical mixtures: The source related Hazard Quotient (HQS) and Hazard Index (HIS) and the adversity specific Hazard

Index (HIA)’, *Toxicology Reports*, 6 (June), pp. 632–636. doi: 10.1016/j.toxrep.2019.06.010.

Gupta, S. K. *et al.* (2018) ‘Multivariate analysis and health risk assessment of heavy metal contents in foodstuffs of Durban, South Africa’, *Environmental Monitoring and Assessment*, 190(3), pp. 1–15. doi: 10.1007/s10661-018-6546-1.

Habte, G. *et al.* (2016) ‘Elemental profiling and geographical differentiation of Ethiopian coffee samples through inductively coupled plasma-optical emission spectroscopy (ICP-OES), ICP-mass spectrometry (ICP-MS) and direct mercury analyzer (DMA)’, *Food Chemistry*, 212, pp. 512–520. doi: 10.1016/j.foodchem.2016.05.178.

Kharazi, A. *et al.* (2021) ‘Human health risk assessment of heavy metals in agricultural soil and food crops in Hamadan, Iran’, *Journal of Food Composition and Analysis*, 100 (November 2020), p. 103890. doi: 10.1016/j.jfca.2021.103890.

Kiran, Bharti, R. and Sharma, R. (2021) ‘Effect of heavy metals: An overview’, *Materials Today: Proceedings*, 51, pp. 880–885. doi: 10.1016/j.matpr.2021.06.278.

Kucich, D. A. and Wicht, M. M. (2016) ‘South African indigenous fruits - Underutilized resource for boosting daily antioxidant intake among local indigent populations?’, *South African Journal of Clinical Nutrition*, 29(4), pp. 150–156. doi: 10.1080/16070658.2016.1219470.

Lebelo, K. *et al.* (2021) ‘Chemical Contamination Pathways and the Food Safety Implications along the Various Stages of Food Production : A Review’, *International Journal of Environmental Research and Public Health*, 18(11). doi: https://doi.org/10.3390/ijerph18115795.

Lizardi, N. *et al.* (2020) ‘Human Health Risk Assessment from the Consumption of Vegetables Grown near a Copper Smelter in Central Chile’, *Journal of Soil Science and Plant Nutrition*, 20(3), pp. 1472–1479. doi: 10.1007/s42729-020-00226-w.

Loi, N. N. *et al.* (2018) ‘The Effect of Cadmium Toxicity on the Development of Lettuce Plants on Contaminated Sod-Podzolic Soil’, *Russian Agricultural Sciences*, 44(1), pp. 49–52. doi: 10.3103/s1068367418010111.

Marguí, E. *et al.* (2021) ‘ Determination of essential elements (Mn, Fe, Cu and Zn) in herbal teas by TXRF , FAAS and ICP-OES ’, *X-Ray Spectrometry* (May), pp. 1–10. doi: 10.1002/xrs.3241.

McHiza, Z. J. *et al.* (2015) ‘A review of dietary surveys in the adult South African population from 2000 to 2015’, *Nutrients*, 7(9), pp. 8227–8250. doi: 10.3390/nu7095389.

Mehri, F. *et al.* (2021) ‘The concentration and health risk assessment of nitrate in vegetables and fruits samples of Iran’, *Toxin Reviews*, 40(4), pp. 1215–1222. doi: 10.1080/15569543.2019.1673424.

National Department of Health (2018) *Regulations Relating to Maximum Levels of Metals in Foodstuffs*. Pretoria: Government Printer, South Africa.

Nuapia, Y., Chimuka, L. and Cukrowska, E. (2018) ‘Assessment of heavy metals in raw food samples from open markets in two African cities’, *Chemosphere*, 196, pp. 339–346. oi: 10.1016/j.chemosphere.2017.12.134.

Okop, K. J. *et al.* (2019) ‘Low intake of commonly available fruits and vegetables in socio-economically disadvantaged communities of South Africa: Influence of affordability and sugary drinks intake’, *BMC Public Health*, 19(1), pp. 1–14. doi: 10.1186/s12889-019-7254-7.

Oliveri Conti, G. *et al.* (2020) ‘Micro- and nano-plastics in edible fruit and vegetables. The first diet risks assessment for the general population’, *Environmental Research*, 187 (May), p. 109677. doi: 10.1016/j.envres.2020.109677.

Park, Y. M. *et al.* (2019) ‘Determination of macro and trace elements in canned marine products by inductively coupled plasma – optical emission spectrometry (ICP-OES) and ICP—mass spectrometry (ICP-MS)’, *Analytical Letters*, 52(6), pp. 1018–1030. doi: 10.1080/00032719.2018.1510938.

Proietti, I., Frazzoli, C. and Mantovani, A. (2015) ‘Exploiting Nutritional Value of Staple Foods in the World’s Semi-Arid Areas: Risks, Benefits, Challenges and Opportunities of Sorghum’, *Healthcare*, 3(2), pp. 172–193. doi: 10.3390/healthcare3020172.

Rai, P. K. *et al.* (2019) ‘Heavy metals in food crops: Health risks, fate, mechanisms, and management', *Environment International*, 125, pp. 365–385. doi: 10.1016/j.envint.2019.01.067.

Ripanda, A. S. *et al.* (2022) 'A Review on Contaminants of Emerging Concern in the Environment : A Focus on Active Chemicals in Sub-Saharan Africa'. *Applied sciences*, 12 (56), pp. 2–30. https://doi.org/10.3390/app12010056.

Sauder, D. C. and DeMars, C. E. (2019) 'An Updated Recommendation for Multiple Comparisons', *Advances in Methods and Practices in Psychological Science*, 2(1), pp. 26–44. doi: 10.1177/2515245918808784.

Schönfeldt, H. C., Gibson, N. and Vermeulen, H. (2010) 'The possible impact of inflation on nutritionally vulnerable households in a developing country using South Africa as a case study', *Nutrition Bulletin*, 35(3), pp. 254–267. doi: 10.1111/j.1467-3010.2010.01837.x.

Tongesayi, T. *et al.* (2013) 'Daily bioaccessible levels of selected essential but toxic heavy metals from the consumption of non-dietary food sources', *Food and Chemical Toxicology*, 62, pp. 142–147. doi: 10.1016/j.fct.2013.08.052.

U.S. EPA (2012) *Sustainable Futures / P2 Framework Manual 2012 EPA-748-B12-00113. Quantitative Risk Assessment Calculations*, *EPA Sustainable Futures – P2 Framework Manual 2012 EPA-748-B12-001*.

- Zulkafflee, N. S. *et al.* (2022) 'Heavy Metal Contamination in *Oryza sativa L.* at the Eastern Region of Malaysia and Its Risk Assessment'. International Journal of Environmental Research and Public Health, 19 (2):7 39. doi: 10.3390/ijerph19020739

CHAPTER 10: CONCLUSION

A comprehensive overview of food contamination and surveillance in the food production chain: A narrative synopsis

10.1. Introduction

This study was grounded by the argumentative discourse, i.e., the researcher attempted to use evidence to convince the reader about the rising threat caused by foodborne chemicals in the food chain. Furthermore, it aimed to add theoretical contributions to the body of knowledge regarding materials and methods, literature framework and research findings to generate further research streams. This chapter summarizes the key findings in the context of Environmental Health. In addition, it highlights the research study objectives and explains its implications for theory and practice. Furthermore, it shows the contributions, limitations and further research questions arising from this thesis.

10.2. The Environmental Health context

Environmental Health is a branch of public health devoted to studying the interaction between human beings and the natural environment, including anthropogenic activities. The prevention of adverse environmental factors to human health and the protection of the environment is essentially the ultimate goal (Musoke *et al.*, 2016). Food is part of the environment and thus contributes significantly to the distribution of diseases when contaminated. Some of these diseases are naturally zoonotic, which can be transmitted from animals to humans. Therefore, the association between human beings and food animals should be controlled. In addition, apart from the microbiological quality of food, special consideration of foodborne chemical contaminants also pose a severe threat to public health.

Environmental Health as a profession is interdisciplinary that allows EHPs to collaborate with different industries and food production departments. The food industry contributes significantly to various foodborne diseases globally. Meat and meat products specifically are extensively consumed worldwide. The challenge lies in the processing systems and hygiene requirements to protect consumers (Musoke *et al.*, 2016; Riccioli *et al.*, 2020). Therefore, it is imperative to regulate such industries to curb the impact of unwholesome products on communities. In worst-case scenarios, the same communities might be immune-compromised due to other social factors.

10.3. Evidence-based decision-making in Environmental Health

The scope of Environmental Health has broadened since the 19th century. Essentially, the discipline is engrained in the social determinants of health as elaborated by the World Health Organization (Dhesi and Stewart, 2015). This broadened approach to solving public health problems further expanded food safety matters. Environmental Health differs from other public health occupations due to the incorporation of the enforcement or regulatory (statutory) function. This often creates a disconnect between policy implementation and the actual practice. Dhesi and Stewart (2015) describe the inability to influence policymakers about the "legitimacy and cost-effectiveness of proactive actions" as unfortunate. This is a result of the short-term, usually difficult-to-measure, complex public health issues faced by Environmental Health Practitioners.

Environmental Health functions and outcomes are generally difficult to evaluate due to the time factor. The programmes and interventions usually take place over a long period, which can be resource intensive; thus, affecting funds. Different methods are applied through experiments. However, EHPs do not record the findings or innovations except in their mandatory monthly reporting (Dhesi and Stewart, 2015). This is problematic if the reports are not shared with the broader scientific community.

10.4. Effects of waste on the contamination of food sources

Despite the reports on the environmental impacts of municipal waste and sources, the generation of waste is still rising due to the global demand for food. Whilst this has presented opportunities for innovation, the new technologies potentially pose another problem in contaminating food sources. The trace metal contamination caused by heavy metals may eventually leach into the food chain through groundwater and direct exposure is a challenge. This can be controlled with biosurfactants which are alternatives to invasive technologies. However, extensive research is needed to ascertain the possible mass production of biosurfactants.

Microplastics are emerging threats to human health. Research shows that a large body of research exists in marine environment studies; however, there has not been much progress regarding the effect of microplastics on human health. This presents challenges to public health officials and the food industry to assess the impact of microplastics on health. Essentially, risk assessments using human subjects need to be conducted on these persistent pollutants to allow policymakers an opportunity to tackle the environmental health risk associated with these contaminants.

10.5. The introduction of contaminants in the food chain

The food industry is sensitive to environmental pollution. Fresh produce, which includes fruits and vegetables, are exposed to contaminants in multiple ways (water, air, soil, chemical spills, etc.). It is, therefore, vital to study the exposure pathways to curb the impact of pollutants on the food chain. There is a need to determine the threshold to detect various chemicals, even at low concentrations. Moreover, the types of exposure must be studied and compared across multiple geographies and cultures, depending on the food consumed. This is necessary for countries that are agriculturally focused.

10.6. The surveillance of foodborne diseases and chemical contaminants

Food contamination and surveillance studies are progressing considerably, even though there is room for improvement. Global public health and surveillance have been under strain due to the emergence of diseases and the rise of chemical contaminants in foods. These ultimately have an adverse economic impact and cause further disturbances in the food industry. The globalisation of trade and environmental factors are major contributors to food safety risks in the food production chain.

The inception of technology in the surveillance of food contamination aims to simplify operations in the food and manufacturing sector. Thus, the field of computer science and chemistry has been pivotal in addressing the shortfalls of the public health fields. The food industry has been adopting machine learning and robotic technologies to minimise contamination and detect contaminants of various origins. Not only has cost-effectiveness been achieved, but there has also been a significant increase in food production. The adoption of technologies has benefited developing countries that rely on agriculture for sustenance and upholding the gross domestic product.

10.7. Advances in surveillance systems and their application

In 1854, the renowned Dr John Snow, during the cholera outbreak in London, demonstrated a pattern through a dotted map that showed the cause of illness could be attributed to the water pump in Broad Street (Carpenter, 2011; Smith *et al*., 2015). To this day, influential public health authorities consistently recommend case locations during outbreak investigations. Public health authorities constantly need to collect, analyse and disseminate information to relevant sectors (Chang, 2019). Similarly, in foodborne surveillance, vital information needs to be used to assess the incidence and prevalence of specific pathogens causing illnesses (Lee, 2017). Furthermore, taking into consideration the high mortality rate reported by the World Health Organization, i.e., 430 000 deaths caused by foodborne diseases, the importance of surveillance activities in food control cannot be underestimated (Lee, 2017).

Ford *et al*. (2015) described different types of foodborne disease surveillance, which cannot take place at the same time, due to their distinct features and the need for different resources. Firstly, event-based surveillance is perceived as less resource-intensive due to the informal nature of the data sources, such as social media. Secondly, indicator-based surveillance is a more recognised method due to the use of routine surveillance data. Lastly, the integrated food chain is complex due to the use of data sources from different sectors that need integration. Moreover, this type of surveillance is expensive and requires sustainable resources. Ford and colleagues suggested a tiered approach with elements of all three types since no single approach can offer all the required information. This will need to be supplemented by big-data mining and synthesis for effective evidence-based decision-making (Jin *et al*., 2020). This is further supported by Lee (2017) who mentioned that such systems would be capacitated in terms of human resources and complex digital systems to handle the immense volumes of data.

In South Africa, most foodborne diseases are notifiable. This means there must be clinical diagnosis and reporting by health authorities. This notification of diseases helps countries to identify outbreaks to determine epidemiological trends (Ford *et al*., 2015; Tchatchouang *et al*., 2020). Data can also be collected from central information systems; notably, Notifiable conditions headed by the Department of Health and Infectious diseases, supervised by the

National Institute for Communicable Diseases. The NICD (NICD, 2015) critically discusses how systems, such as the above-mentioned should be in place to guide evidence-based decision-making. As a precaution, they warn against delayed delivery of time-sensitive information that alters the information flow from system managers to employees at the operational level. With the role of the NICD in mind, it would be beneficial to have a separate unit focusing on chemical contaminants that have been rising in recent years.

10.8. Implications for theory and practice

The research findings arising from this study have practical and theoretical implications. This research can serve as a call for researchers and EHPs, and environmentalists to explore environmental exposures further. These assessments need to be targeted towards food safety, especially at the beginning of food production. One implication for research arises from findings that heavy-metal exposures are problematic in developing nations and may affect the food industry significantly due to polluted environments serving as a vehicle for contamination. This should stimulate debates about using more robust systems and techniques in public health when measuring environmental exposures. The SEM-EDS technique presented in chapter 2 showed that the technique is not sensitive to detect heavy metals in low concentrations for certain trace metals, thus the IC-OES is preferable when conducting elemental analysis. This may open channels to alternative ways of detecting how trace metals manifest in the food industry, as well as potential interventions. This thesis showed the extent of chemical contamination (non-essential metals) in selected vegetables in Bloemfontein. The hypothesis stating that vegetables sold at Bloemfontein fresh-produce markets have heavy-metal concentrations exceeding the permissible limits, and the hazard quotients and hazard index will be ≥ 1, is therefore rejected as per the results shown in Chapter 9. There is sufficient evidence showing that the sampled vegetables comply with *Codex Alimentarius* standards for metals in foodstuffs.

10.9. Future studies and direction

- Financial implications of using OES analytical procedures as a baseline for Environmental Health investigations.
- Risk assessments for both essential and non-essential metals in food and how they are transported in the food chain.

- The design of robust monitoring and surveillance tools for chemical contamination in the food chain.

10.10. Research summary and contributions

- Using intelligent systems in the surveillance of foodborne diseases.
- In-depth understanding of chemical contamination pathways.
- Methods for remediating polluted environments in relation to food safety.
- Understanding the risk-assessment principles when detecting heavy-metal exposure in vegetables.

10.11. References

Carpenter, T. E. (2011) ‘The spatial epidemiologic revolution: A look back in time and forward to the future’, *Spatial and Spatio-temporal Epidemiology,* 2(3), pp. 119–124. doi: 10.1016/j.sste.2011.07.002.

Chang, K. (2019) ‘Geographic information system technology’, *The International Encyclopedia of Geography*. John Wiley & Sons, Ltd. doi: 10.1002/9781118786352.wbieg0152.pub2.

Dhesi, S. and Stewart, J. (2015) ‘The Developing Role of Evidence-Based Environmental Health: Perceptions, Experiences, and Understandings From the Front Line’, *SAGE Open*, 5(4). doi: 10.1177/2158244015611711.

Ford, L. *et al*. (2015) ‘Approaches to the surveillance of foodborne disease: A review of the evidence’, *Foodborne Pathogens and Disease*, 12(12), pp. 927–936. doi: 10.1089/fpd.2015.2013.

Jin, C. *et al*. (2020) ‘Big Data in food safety - A review’, *Current Opinion in Food Science*, 36, pp. 24–32. doi: 10.1016/j.cofs.2020.11.006.

Lee, B. (2017) ‘Foodborne disease and the need for greater foodborne disease surveillance in the Caribbean’, *Veterinary Sciences*, 4(3). doi: 10.3390/vetsci4030040.

Musoke, D. *et al*. (2016) ‘The role of environmental health in One Health: A Uganda perspective’, *One Health*, 2, pp. 157–160. doi: 10.1016/j.onehlt.2016.10.003.

National Institute for Communicable Diseases *et al*. (2015) ‘Africa’s Health Burden: Assessing the Role of Community in Health Care Delivery’, BMC Public Health, 6(1), pp. 1–8. doi: 10.1186/1471-2458-4-29.

Riccioli, F. *et al*. (2020) ‘Willingness to pay in main cities of Zheijiang provice (China) for quality and safety in food market’, *Food Control*, 108 (May 2019), p. 106831. doi: 10.1016/j.foodcont.2019.106831.

Smith, C. *et al*. (2015) ‘Spatial methods for infectious disease outbreak investigations: Systematic literature review’, *Euro Surveill*., 20(39), pp. 1–21. Available at: www.eurosurveillance.org

Tchatchouang, C. D. K. *et al*. (2020) ‘Listeriosis outbreak in south africa: A comparative analysis with previously reported cases worldwide’, *Microorganisms*, 8(1). doi: 10.3390/microorganisms8010135.