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Pesticides and Their Effects on Gut Microbiota: A Comprehensive Review of Environmental and Health Consequences

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ABSTRACT

An increasing use of pesticides in agriculture is considered as the dangerous hazard to environment, human health, and sustainability. The effects of pesticides on organisms include decline in the amount of phytoplankton and zooplankton, development of resistance in pests and negative impacts on pollinators. These chemical residues too interfere with the biogeochemical cycles, reduce the microbial count in the soil, and are anti-neo plastic and carcinogenic in nature in different species. Concerning human health effects, the exposure to these chemicals cause cancer, deterioration of neurodevelopment, reproductive disorders as well as immune disorders. Besides, the action of pesticides is aimed at destroying both the beneficial bacteria of the gut microbiota, thus causing obesity and diabetes. The measures required for these problems include regulation and farmer awareness and schooling to stop the contamination from piling up in water bodies. Some strategies include microbial degradation, pesticide degradation and improvement of the population of microorganisms in the soil. Organic farming and sound policies are important to maintain and improve the earth's condition, uphold the companies' standards set by the legal frameworks, and sustain the quality of life. Therefore, the impacts of pesticides on microbiota and the interactions of hosts and microbes need to be analyzed to devise appropriate solutions. These efforts are very useful for dealing with possible health threats and ensuring environmentally friendly farming.

Keywords: Pesticides, Gut Microbiota, Biodegradation, Obesity, Diabetes.

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1.INTRODUCTION

Infact, due to the necessity of rising yields to feed the quickly expanding global population, there has been steady fortification of pesticides (Dhaliwal *et al.*, 2022). This has the effect of leading to presence of pesticide residues in foods as well as the environment and this is dangerous to the health of human beings as well as posing threats to the balance of ecosystems (Sharma et al. , 2023). Jacobs complains that besides the target pests, pesticides also subjugate benign beings, which, as the ultimate predators in the trophic pyramid, are humans (Ukhurebor et al., 2021). Different researches conducted have found out the presence of pesticide residues in human blood and urine and they are said to cause several ailments including cancer, diabetes, hormonal imbalance, asthma, metabolic diseases, and neurotoxicity. Long-

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term exposure has also been found to cause teratogenicity resulting to low birth weight, developmental abnormalities, diseases and mortality (Devi et al. , 2022).

The current studies show that pesticides influence the balance of gut microbiota which is essential in the functioning of immune system and release of hormones needed for various activities in the body (Yoo et al., 2020). It is now recognized that altered GI microbios said to be in connection with obesity, colon cancer, type two diabetes, and other metabolic syndromes (Riedo, 2021). These metabolic disorders are exacerbated by pesticides because they affect the functioning of the intestinal microbiota (Mesnage et al. , 2022).

However, the presence of pesticide residues is not only a threat to human health but also to the environment (Ali et al., 2020). These residues can remain on or within the food products after harvest and due to environmental pollution; this poses health risks to the consumers (Matsuzaki et al. , 2023). Persistent use of pesticides has resulted into their build up in the soils and water sources and hence, inclusion of these chemicals in the food chain. Since coexistence of multiple pesticide residues in soils is the reality of today’s environment, consequently, the strategies under environmental risk assessment should be revolutionized not only to reduce the risks posed to life in the soil but also to life beyond it (Ortiz-Hernández et al. , 2013).

Continuation of monitoring of Pesticide Residues and toxicity assessment on a higher number of species of soils will be the successful efforts that need to be employed for more effective risk analysis (Meng et al. , 2020). The gut microbiota introduce trillions of bacteria residing in the human gastrointestinal tract that determine health status. In physically it plays a role in immune system regulation, metabolism, and the development and function of the brain. It is for this reason that the general wellbeing can be deeply affected each time there is a version of the gut microbiota (Cresci and Izzo, 2019).

Interest in the effects of pesticides on altering gut microbiota’s composition and functionality has surged in the last few years. The gastrointestinal tract as a biological and physical barrier is the initial organ system that gets into contact with the pesticides in contaminated foods (Sharma et al. , 2023). Several works have confirmed the strong association between gut microbiota and the condition of the environment. For example, studies conducted on mice discovered that chlorpyrifos which is a pesticide causes a shift on gut flora making the consumers develop insulin resistance and obesity (Ueyama et al. , 2022).It is essential to investigate how pesticides alter the composition of gut microbiota under different experimental settings in order to study how these agents modulate the health of their host. A study shows that several pesticides, namely fungicides and insecticides, shift the sample balance of the gut microbiota (Odintsova, Klimenko and Tyakht, 2022). Such alterations lead to shifts in the composition of the individual bacterial genera and a decrease in the levels of microbial heterogeneity (Tu et al. , 2020).

In addition, the utilization of pesticides can have an impact on thinking ability due to the effect in a way of altering signal between the gut microbes, stomach, and the brain. As research proves that, pesticide affects the cognitive abilities negatively, it is still uncertain if such behavioral shift is caused by the change in gut microbiota or combined factor (Yuan et al. , 2019).

There are direct and indirect on gut flora where pesticides come into contact with it. They may consciously change the types and levels of microbes and the microbial products, which will cause chain reactions on the body and affect the enzyme genes and enzymes in intestines and liver (Ueyama et al. , 2022). Due to the effects that pesticide exposure has been shown to have on the flora of the gastrointestinal tract, it is deemed necessary that this relationship be explored in further detail. It is pertinent to note functional change and the composition of gut flora, it may be useful for biomarkers for pesticide poisoning (Benitez and Ramírez-Vargas, 2021). The resolution required for the evaluation of the alters in microbial strains and species following pesticidal exposure are best done by 16S rRNA analysis and shotgun metagenomics (Tu et al. , 2020).

Since the use of pesticide caused negative impacts on human health, it is vital to look for the alternative which includes the biopesticides, RNA based biopesticides (Halder et al., 2022). These methods could help lessening the negative effects on human beings' wellbeing and encourage better forms of farming. Nevertheless, more studies are indispensable to set direct correlations between the composition of gut microbiota and the related metabolites to the pesticides to adequately evaluate pesticide toxicity (Sharma et al. , 2023).

1.1.Mechanisms of Pesticides and Gut Microbiota Interactions

The gut microbiota contains bacteria, fungi, and viruses that are found in humans' gastrointestinal system that positively impact their health. These factors or rather the modulators include age, diet, chemical exposure, antibiotics, and even environment including the use of pesticide (Sharma et al. , 2023). Some new studies have established the possible effects of pesticide on the health of people including those of bacterial flora in the gut.

Pesticides consists with a wide range of chemicals utilized to control pests inclusive of insects, weeds, molds, bacteria and other pests; these control chemicals include insecticides, herbicides, fungicides and bactericides have caused some concern due to their usage and impact on other organisms including man (Miller, Ferreira and LeJeune, 2022).

It has been pointed out that the exposure to pesticide residues in the environmental or in diet might affect the composition and functions of gut microbiota (Mesnage et al. , 2022).Thus, it has been shown that pesticides affect the gut microbiota through diverse signaling mechanisms which impact the microbial growth and activity (Gois et al. , 2023). For example, herbicides can change the taxonomic characteristics of gut bacteria; that is, their degree of richness and abundance. As recorded in other experiments, pesticides have consequences to the host's microbiota that has a role to produce polyamines and SCFA (Matsuzaki et al. , 2023).

In addition, surveys done in the current years depict that pesticide use leads to dysbiosis in the microbiota of the gastrointestinal tract making them less stable and are associated with pathogenic states. This dysbiosis is rarely corrected and is linked to obesity, type 2 diabetes, IBS, allergies, neurodegenerative diseases, tumors, neurological disorders and inflammation (Ueyama et al. , 2022) as showed in (figure 1).

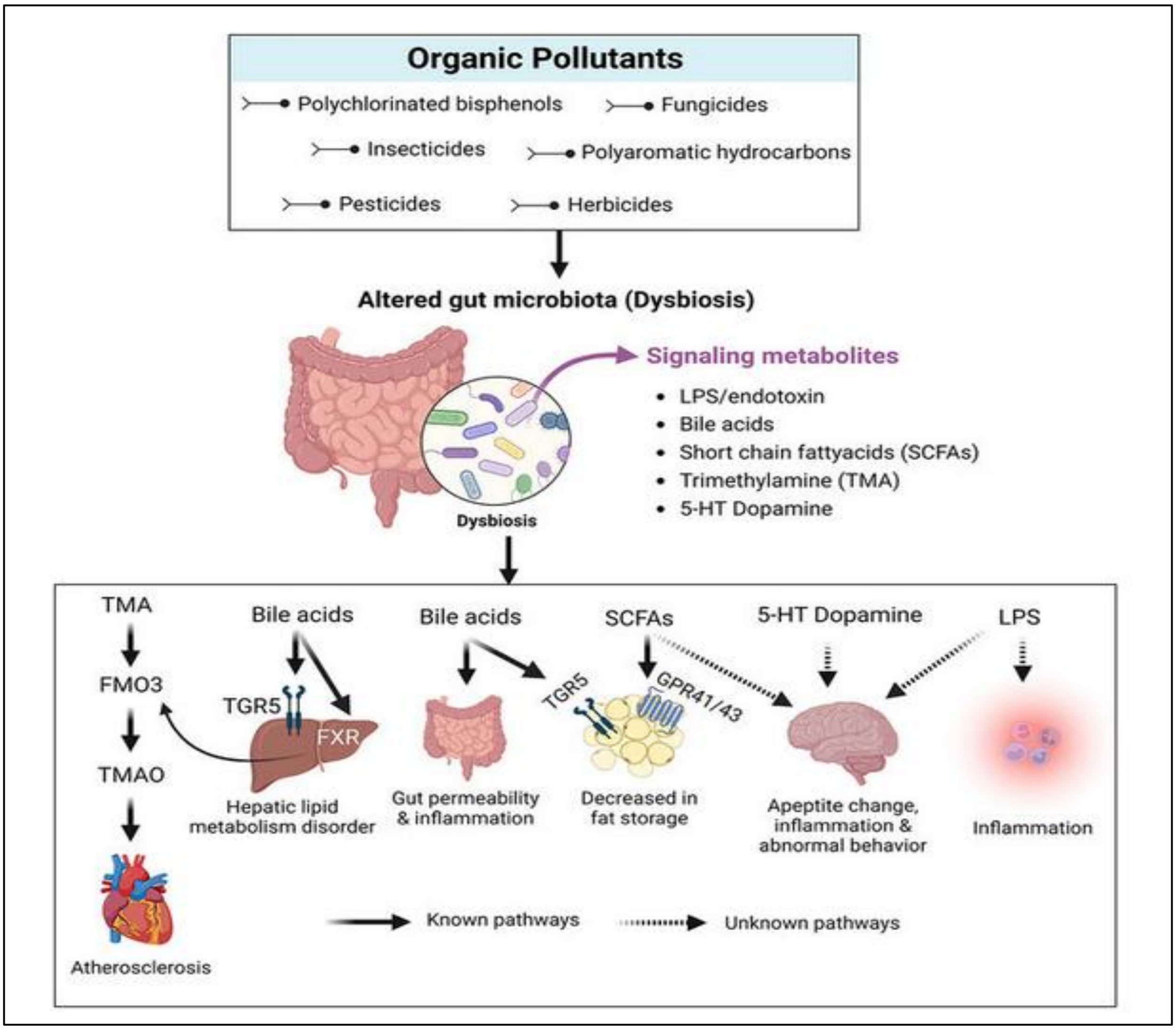

Figure 1: The Effect of Pesticides and Subsequent Outcomes on Gut. (Sharma et al., 2023).

Stressing new data from the contemporary researches is significant to investigate possible health effects linked to the gut microbiome-pesticide interactions (Giambò et al. , 2021). The inhabitants of the gastrointestinal tract called microbiota are considered to be a crucial component of human health and are a rapidly developing topic. Thus, it calls for the filling of gaps in knowledge of the changes in microbial composition and function due to exposure to specific pesticides in order to understand ways of managing the possible adverse health consequences of exposure to pesticides (Kim, Kabir and Jahan, 2017). With a plethora of human and animal studies presenting the impacts of pesticide interference with the gut microbiota and its functionality, literature on the mechanism of the contextual changes remains scarce (Adak and Khan, 2018). To address these issues, more extensive knowledge will be deservedly to consider the above-listed aspects by the pesticides-induced changes in the gut microbiota and regarding how such changes might affect behavioral changes, more information must be gathered in future researches (Syromyatnikov et al. , 2020).

In conclusion, based on the information on how pesticides influence not only the target pests but also the organisms co-existing in the ecosystem including humans via altering the gut microbiome, it is imperative to do so (Hall et al., 2019). Solutions to these problems will be crucial for formulating measures that will reduce health hazards connected with the use of pesticide and, at the same time, ensure the continuing sustainability of the agricultural yields (Damalas and Koutroubas, 2018).

1.2.Host Health Effects

Pesticides are known to possess a significant effect on human gut microbiome that leads to various health complications. The continued and inevitable use of pesticides is a risk factor, particularly to other organisms, with humans being the most affected since they reside at the apex of the pyramid (Kulcsarová et al. , 2023). According to the research done, chemical residues of pesticide in the blood and urine samples have been found to be associated with multiple diseases like cancer, diabetes, hormonal disorders, asthma, metabolic diseases, Neotoxity and so on (Sharma et al. , 2023). Similarly, prolonged exposure has also been observed to have teratogenic effects such as low birth weight, impaired growth, diseases, and death (Mesnage et al. , 2022).

Several studies have been documented showing a correlation between pesticides and a variety of diseases and illnesses (Mostafalou and Abdollahi, 2013). From the literature, there is evidence that proves that pesticides trigger the formation of cancer and its aggravation. Also, there are indicators that they can increase the risk of diabetes development. Pesticides have also been shown to increase hormonal issues and asthma in humans. Further, pesticide containing neurotoxic effects (Matsuzaki et al , 2023).

The gut microbiota contributes to the synthesis of hormones and the immune response of the host, hence host health. Gut microbial dysbiosis causes different diseases which include; metabolic syndrome, obesity, colon cancer, and diabetes. Influence on the gut microbiota can also be unfavorable in cases when pests affect host health (Ortiz-Hernández et al. , 2013). From a food safety perspective, there is significant worry on the impact of Pesticides residues on gut microbiota and subsequent impact on health of individuals and Non Communicable Diseases. Dietary regimens, chemicals, antibacterial agents, environment pollutions, aging are some of the factors affecting the composition of gut microbiota (Ueyama et al. , 2022).

Therefore, the use of pesticides also has an impact on gut microbiota, and these impacts are manifested in the form of neurotoxicity, hormonal imbalances, asthma, metabolic diseases, and cancer. There are several issues which arise from the extensive application of pesticides for agriculture among them being public health as showed in (Figure 2).

Figure 2: Routes of exposure to pesticides (Tudi et al., 2022).

2.1. Correlations between Pesticide Exposure and Chronic Diseases

The current studies exploring the long-term impact of pesticides on human health have noted the alteration of gut bacteria as a critical issue. Research has shown that due to the immense and compulsory application of pesticides, there is the likelihood to damage the non-target species which include man. Remnants of the pesticides in produce that consumers consume are very dangerous and have been associated with diseases such as cancer, diabetes hormonal imbalances, asthma, metabolism complications, and neurotoxicity. Similarly, long term exposure to pesticides contributes to teratogenic effects where the birth weight is low, abnormal growth, illnesses and hence, mortality (Van Der Werf, 1996).

Gut microbiota can be considered as the second brain that is responsible for maintaining normal physiological processes due to the secretion of hormones and regulation of the immune system. Alterations in the microbiota result in several disorders including obesity, colon cancer, diabetes and other metabolic disorders. Influencing the composition of gut microbiota, pesticides are involved in the development of metabolic diseases in hosts (Shah, 2021). Professional exposure to these pesticides has been reported in different studies to reduce the alpha diversity of the microbial community in the gut, and lead to different beta diversity also (Shah, 2021).

There are earlier papers that have speculated that those who are exposed to OP have health issues such as low IQ, learning disabilities, asthma, obesity, and low lung function. An understanding of how OP exposure can cause such effects is still limited, although it has recently been confirmed that gut microbiota contributes to human health (Mahmood et al. , 2016). Thus, dietary choices are proven to affect the rate of metabolism of the microorganisms in the gut and their effects on the health of an individual. Issues have arisen regarding how eating food treated with pesticide can cause alterations in the composition of the gut bacteria that in turn leads to chronic diseases (Hu et al. , 2015). The consumption of fruits and vegetables that are grown in a manner that is conventional means that the individual is exposed to pesticides with unfathomable effects on health after long-term use (Devi et al. , 2022).

Therefore, alterations in gut microbiota brought by pesticide effects are potential threats to the safety of human health in the future (Utembe and Kamng'ona, 2021). On the basis of the given theories and existing knowledge on the consequences of pesticide exposure, it is critical to study how these disturbances have different impacts on health (Sharma et al. , 2023).

It is important to establish the correlation between pesticides and chronic diseases since pesticide have been found to have an impact on several chronic diseases (Gangemi et al., 2016). Pesticide exposure has also been linked to the following obvious adverse health consequences including neurodevelopmental abnormalities, cancer, neurological disorders, and respiratory diseases (Mesnage et al. , 2022). High pesticide use can cause sterility problems; birth anomalies and stillbirths, spontaneous fetal death, and infertility difficulties (Kalyabina et al. , 2021). In addition, effects of long term exposure to pesticide has also disclosed liver damage as well as blood disorders. Pesticide sensitivity can therefore be characterized by increased sensitivity to light, sound or touch, dizziness, shaking or convulsions, tendency to faint, vomiting, confusion and excessive worry. Also, studies indicate that pesticide may lead to several neurological illnesses such as loss memory and coordination, poor eyesight, and poor motor functions (Kim et al. , 2017).

Because the nervous system is affected, one is likely to worry about other side effects that could be long term. Long-term pesticide use has impacts on the surrounding environment which cannot be overlooked in favor of the direct effects on people (Crivellente et al., 2019). Pesticides have adverse effects on soil, water, crops, and the air because of abuses through excessive use (Shah, 2021). The following acute and chronic health effects can affect all people regardless of their age after coming into contact with pesticides within environment. This demonstrates how pesticides impact several aspects of an environment and human well-being (Syromyatnikov et al. , 2020). It has been established that pesticide exposure cause long term health complications. These relationships are important to decrease the impact of pesticides on human health in the future (Dhankhar and Kumar, 2023).

2.2. Effects on Immune System Function

Comprehensive research studies reveal that pesticide exposure is a major cause of hazardous health effects principally affecting the immune system in the human body (Lee and Choi, 2020). A number of epidemiological investigations have established that pesticide use might lead to an assortment of diseases, including chronic diseases and neurodevelopmental disorders including ASD. Some of the emerging issues based on newest research are focused on the shift in microbiota. In this case, pesticides can stimulate an imbalance of the gut flora, which results in symptoms similar to ASD (Dhouib et al., 2016). Deficiency in these bacteria or the disruption in gut microbiota may affect the synthesis of bacterial metabolites which leads to the occurrence of ASD symptoms. It is also proved pesticide exposure in infancy directly affects the balance of gut microbiota and relate to a higher risk of developing ASD (Yang et al. , 2023).Numerous academics have investigated pesticide exposure's serious consequences, which include chronic diseases contributing to the immunological dysfunction: diabetes, cancer, heart disease, and lung disease (Zhao et al., 2023). Pesticides may also get into the body through topical application, through respiratory system because they are airborne and through consumption of foods rich in pesticides. Low-dose pesticide usage over several years leads towards the development of several immunological sicknesses (Kalyabina et al. , 2021).

Besides, the studies have demonstrated that the long-term effect of pesticide exposure results in genotoxicity and oxidative stress on pregnant women and impacts the pregnancy in terms of caesarean deliveries and preterm births with babies having lower birth weights. Other papers also show toxic pesticide residues in human breast milk, where prenatal exposure affects the health of children in negative ways (Mesnage et al. , 2022). Besides, postnatal exposure was also identified to have negative impact on a child's neuropsychological behavior (Hu et al. , 2015). Previous research on specific agent exposure indicated association of occupationally-acquired pesticides with reproductive disorders and congenital defects through DNA damage. A variety of pest control chemicals; endocrine disruptors affect human fertility, resulting to infertility in female and male (Moreira et al., 2021). That's why long term exposure such as Parkinson's and Alzheimer's diseases, as well as various other kinds of reproductive and respiratory diseases has also been stated (Devi et al. , 2022).

Conclusively, impairment of immune system by pesticide affects the ability with with humans handle chronic diseases and neurodevelopmental disorders, or even result in them (Arab and Mostafalou, 2021). Alterations in gut microbiota as a result of pesticides' effects on the human body are much more significant when considering the long-term effects (Mostafalou and Abdollahi, 2018). From the concern in this regard, the evident link between pesticide exposure and chronic diseases implies further research into how these disruptions cause different poor health outcomes (He et al., 2022).

3. Environmental Implications

3.1. Pesticide Residues

Pesticides are widely used in agriculture, and its pollution of surface water occurs through various processes including; drainage, runoff, leaching, and drift (Devi et al. , 2022). Residues of different groups of pesticides such as organochlorines, organophosphates, carbamates, neonicotinoids, and pyrethroids have been identified in rivers and soil around the world and which are a serious menace to aquatic life. The authors pointed out that in 2008, the European Union's soil contained the following pesticide residues; 83% tested positive for at least one pesticide and 58% had more than one (Ortiz-Hernández et al. , 2013). Among the above residues, glyphosate and its derivatives are most frequently identified and often at high concentrations. Over the years studies done on the river water have revealed high concentrations of several kinds of pesticide residues more so in regions that are being used for agricultural and horticultural farming (Syafrudin et al., 2021).

The impact of pesticide residues on the aquatic ecosystem also negatively affects the lives of human and animals and aquatic ecosystems that Source their drinking water from the water systems. By the suppression of phytoplankton and zooplankton populations, pesticides are known to impact water quality. Moreover, the toxic impacts of pesticides also contain carcinogenic and neurotoxicity to different species of invertebrates, fish, amphibians, insect, and mammals. Pesticides are also a cause of resistance in pests and diseases, as well as reducing the beneficial insects such as pollinators. Also, pesticides affect biogeochemical cycles; they eliminate macro- and microbes and pollute water bodies with pollutants (Karpouzas et al. , 2022).
Therefore, there is good evidence that the capacity of agricultural soils which contain pesticide to affect the structure and composition of soils microorganisms. Pesticides reduced bacterial diversity as well as nitrogen fixation genes and their impact was even higher than that of other management practices (Walder et al. , 2022). Due to this imprudent application, there has been a steady rising in the pesticides residues whereby the ecosystems and the animals are affected since the surface water such as water used for drinking and irrigation are affected. To counter these effects, the legal introduction of protective ordinances and raising the farmer's awareness about the pollution of water sources to minimize the pesticide build-up in water bodies (Jaffar et al. , 2022).

3.2. Biodegradation Approaches

Addressing pesticide contamination requires effective strategies for biodegradation. The primary goal of these strategies is to reduce the environmental burden of pesticide residues by breaking them down into less harmful substances. Various methods and technologies are employed to achieve this (Figure 3), including:

- **Microbial Biodegradation**: Utilizing microorganisms capable of degrading pesticides. This method leverages bacteria, fungi, and yeast that can metabolize pesticide residues into less toxic compounds (Hussain et al., 2016).
- **Phytoremediation**: Employing plants that can absorb, accumulate, and degrade pesticides from contaminated soils and water. Certain plant species have demonstrated the ability to uptake and transform pesticide residues, effectively removing them from the environment (Hussain et al., 2009).
- **Enzymatic Degradation**: Using enzymes produced by microorganisms or plants to break down pesticide residues. Enzymatic methods can be highly specific and efficient, targeting particular pesticide compounds (Qin et al., 2019).
- **Bioreactors**: Implementing bioreactors that use a combination of microorganisms and environmental conditions to enhance the breakdown of pesticide residues. These systems can be designed to treat contaminated water or soil (Ewere et al., 2024).

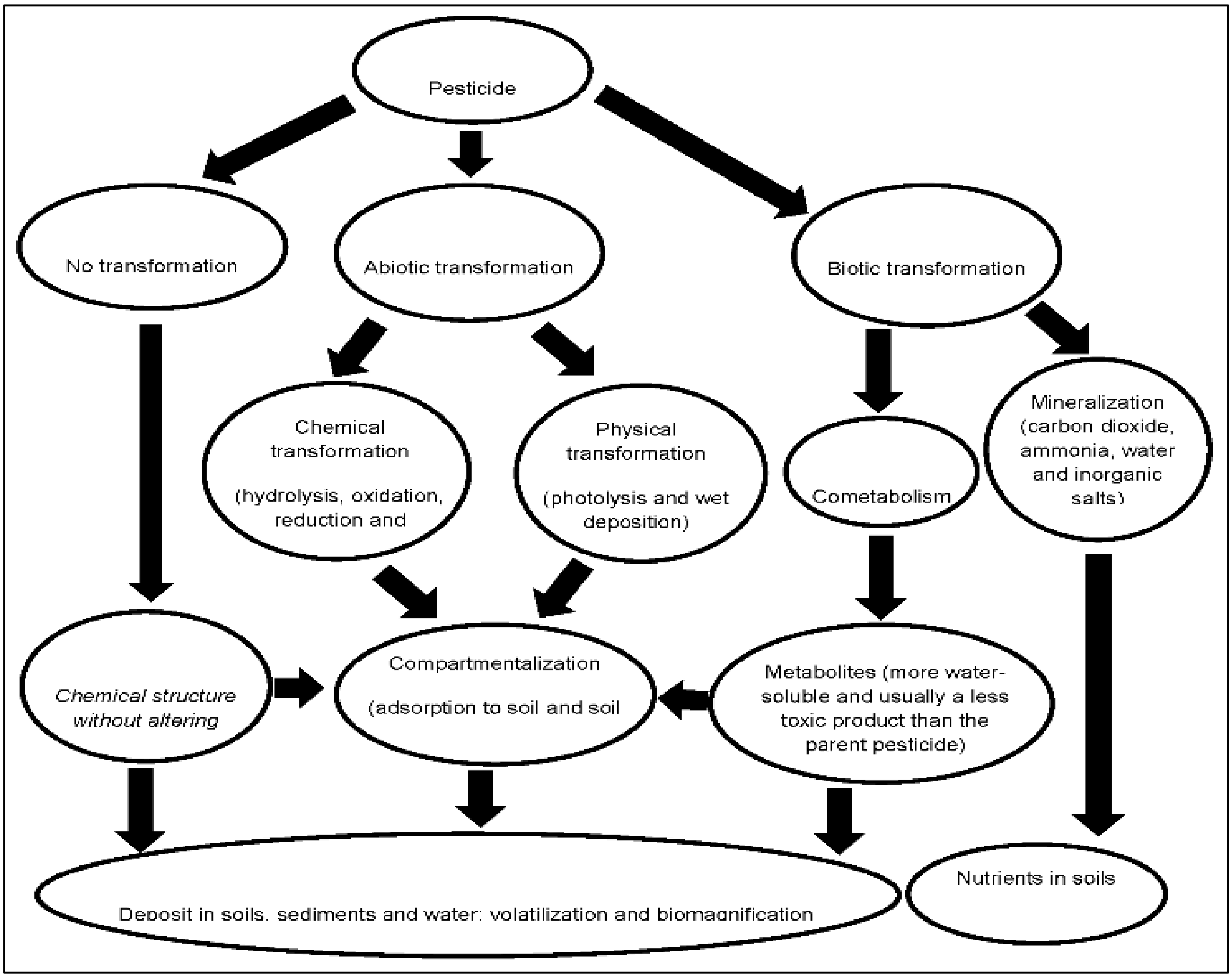

Figure 3: Fate of pesticides in the environment.

Looking at the study that was conducted, it showed that European soil has more than one pesticide residue out of the 83% that had at least one, 58% had two or more pesticide residues (Sehrawat et al. , 2021). These residues are also known to be toxic to aquatic organisms and also influence the microbial activity in the soil; it therefore requires a correct biodegradation mechanism to be implemented to tackle any contaminated environment (Ramírez et al., 2023).

Therefore, it can be seen that pesticides are a strong influence affecting numerous microbiomes belonging to the miscellaneous situated in soil, animals, or within the human body. That is why it is crucial to understand such effects in order to talk about environmental impact, and to improve the activity directed at minimizing the hazardous influence upon the environment and human health. Further research and investigations on the relationships between host-health microbial interactions with regards to pesticide dangerous effects should be conducted to assist in the elimination of the mentioned health effects.

4. CONCLUSIONS

Pesticides are a threat to water and soil, including the organisms inhabiting them, microorganisms in the soil, ecosystems, reduction in the level of bio-diversity, and susceptibility to pests. To humans, pesticides residues cause severe illnesses such as cancer, diabetes and affect the balance of bacteria in the gut that could lead to metabolic and inflammation diseases. To tackle these challenges, it is important to have tighter frames regulating and organic farming methods. Furthermore, efforts must be made to find eco-friendly substrates and expanding research into the effects of pesticides on microbial ecosystems and well-being as to minimize such opportunities and protect the industry from dangerous drawbacks and work towards a more constructive agriculture.

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