

## Review Article

### **Impact of Agrochemicals on beneficial microorganisms and human health**

#### **Abstract**

Agrochemicals, including fertilizers, pesticides, and herbicides, are widely used in agriculture to improve crop yields and protect plants from pests and diseases. There is growing concern over their impact on beneficial soil microorganisms and, indirectly, on human health. This review aims to provide an in-depth analysis of the effects of agrochemicals on soil microbial communities and human health, focusing on recent scientific research and case studies. Exploring various agrochemicals can disrupt microbial diversity, population, and functionality, affecting crucial soil processes and, in turn, ecosystem health. We delve into the pathways of human exposure to agrochemicals and the potential health implications. To mitigate the adverse effects of agrochemicals, the review highlights several alternative approaches, including the use of organic fertilizers and pesticides, precision agriculture, and genetically modified crops. Despite these advancements, research gaps persist in understanding the complex interplay between agrochemicals, beneficial microorganisms, and human health, particularly in the changing agricultural practices and climate conditions. We argue that interdisciplinary, long-term studies are needed to fill these gaps and develop sustainable, health-conscious agricultural practices. The review is intended for researchers, policymakers, and agricultural practitioners seeking to understand and address the environmental and health impacts of agrochemicals.

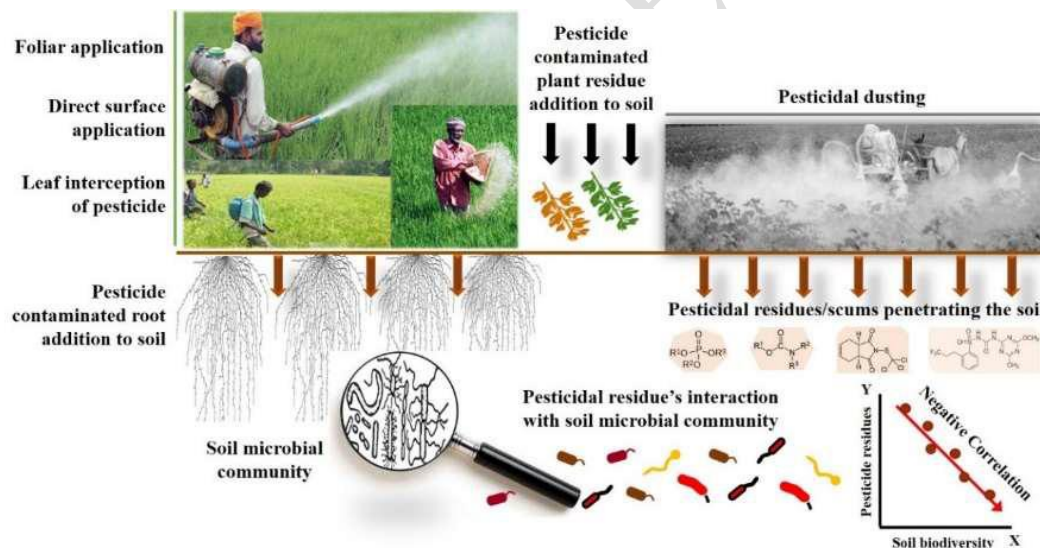
**Keywords:** *Agrochemicals, Soil Microorganisms, Human Health, Sustainable Agriculture, Genetically Modified Crops*

#### **Introduction**

Agrochemicals, also known as agricultural chemicals, are substances used in agriculture to promote plant growth and protect crops from pests and diseases (Damalas & Eleftherohorinos, 2011). These chemicals are classified into various types, including but not limited to, fertilizers, pesticides, plant growth regulators, and soil conditioners (Aktar *et al.*, 2009). These play a pivotal role in modern agriculture by enhancing productivity, ensuring food security, and supporting the global economy (Carvalho, 2017). The use of agrochemicals also raises concerns due to their potential environmental and health impacts. One of the lesser-known but highly significant aspects of this impact is the effect of agrochemicals on beneficial microorganisms. Microorganisms are fundamental to the fertility of the soil and the nutrient availability for plants (Berendsen *et al.*, 2012). They participate in numerous processes, including organic matter

decomposition, nutrient cycling, disease suppression, and plant growth promotion (Philippot *et al.*, 2013). Apart from their crucial role in soil health, beneficial microorganisms, such as certain bacteria and fungi, have significant effects on human health as well. The gut microbiota, for example, is essential for digestion, immune system functioning, and even mental health (Cani, 2018). Disruption of these beneficial microbial communities, either through diet or environmental exposures, could have substantial health impacts.

A growing body of evidence suggests that the use of agrochemicals may be negatively affecting beneficial microorganisms both in the soil and within the human body (Wagg *et al.*, 2019). Understanding the relationship between agrochemicals, beneficial microorganisms, and human health is, therefore, of paramount importance. This review aims to synthesize current knowledge on this topic, elucidate the mechanisms of agrochemical-induced harm, and identify opportunities for further research and mitigation.



**Image 1:** A schematic illustration depicting the response and effects of pesticides on soil microbial communities and biodiversity. (Source: Meena *et al.*, 2020)

## Agrochemicals

Agrochemicals encompass a broad range of substances, each with a distinct role in agricultural management. Fertilizers, including nitrogenous, phosphatic, and potassic types, provide essential nutrients to the soil, thereby enhancing plant growth and productivity (Pahalvi *et al.*, 2021). Pesticides, including insecticides, herbicides, and fungicides, are employed to protect crops from pests and diseases, thereby securing crop yields (Carvalho, 2006). Other agrochemicals, such as plant growth regulators and soil conditioners, fine-tune the growth and developmental processes of crops and improve soil physical properties, respectively (Saraf, 2014). The use of agrochemicals is widespread across the globe, reflecting their crucial role in

modern agricultural practices. In 2018, the global agrochemical market was estimated to be worth \$239.85 billion and projected to reach \$365.16 billion by 2027. This growth is driven by the rising global population and the consequent demand for increased food production.

### Beneficial Microorganisms

Beneficial microorganisms encompass a wide array of bacterial, fungal, protozoan, and algal species that contribute positively to soil health and plant growth (Table 1). Bacteria such as *Rhizobium* and *Azotobacter* contribute to nitrogen fixation, while others like *Pseudomonas* and *Bacillus* species play roles in phosphorus solubilization and biological control of plant diseases (Mohammed, & Toama, 2019). Fungi, including species of Mycorrhiza, enhance nutrient uptake by plants and increase their tolerance to environmental stress (Bahadur *et al.*, 2019). Beyond their soil and plant-related roles, beneficial microorganisms also have significant implications for human health. The human microbiome, comprising trillions of microbial cells, is critical for various physiological functions, including digestion, immune regulation, and even mood regulation (Cryan *et al.*, 2019). Disruptions in these microbial communities are associated with a range of health conditions, from inflammatory bowel disease to mental health disorders (Aden *et al.*, 2019).

**Table:1** Beneficial Soil Microorganisms and their Functions

Type of Microorganism	Example Species	Benefits	References
Bacteria	<i>Rhizobium</i> spp.	Nitrogen fixation, enhances plant growth	Lugtenberg and Kamilova, 2009
Fungi	Mycorrhizal fungi	Improves nutrient and water uptake, promotes plant growth	Smith and Read, 2008
Protozoa	Amoebae, flagellates, ciliates	Regulates bacterial populations, nutrient cycling	Bonkowski, 2004
Algae	Cyanobacteria (blue-green algae)	Nitrogen fixation, soil stabilization	Whitton and Potts, 2007

### Relationship between Agrochemical Use and the Health of Beneficial Microorganisms

Recent research has shed light on the potentially detrimental effects of agrochemicals on beneficial microorganisms. For example, certain pesticides have been shown to decrease the abundance and diversity of soil microorganisms, affecting nitrogen fixation and other key soil processes (Hussain *et al.*, 2009). Agrochemicals can also potentially influence the human microbiome. Exposure to glyphosate, a commonly used herbicide, has been suggested to affect gut microbiota composition, with potential implications for human health (Ruuskanen *et al.*, 2020). The interaction between agrochemicals, beneficial microorganisms, and human health is complex and depends on various factors, including the type and concentration of agrochemicals used and the specific microbial communities present. Understanding this interplay is crucial for making informed decisions about agrochemical use and managing their potential impacts on

environmental and human health.

### Impact of Agrochemicals on Beneficial Microorganisms

Extensive research indicates that agrochemicals, particularly pesticides and fertilizers, can have a profound impact on soil microorganisms (Table 2). Pesticides, such as neonicotinoids, have been found to decrease the abundance and diversity of certain soil microbial communities (Zhao *et al.*, 2020). Similarly, repeated application of nitrogenous fertilizers can lead to an imbalance in microbial communities, favoring certain bacteria over others (Leff *et al.*, 2015).

**Table:2** Impact of Selected Agrochemicals on Beneficial Soil Microorganism

Agrochemical	Beneficial Microorganism	Impact
Glyphosate (herbicide)	Rhizobia (nitrogen-fixing bacteria)	Can inhibit growth and symbiotic performance (Santos & Flores, 2018)
Mancozeb (fungicide)	Mycorrhizal fungi	Can reduce colonization and impair function (Sabatino <i>et al.</i> , 2020)
Imidacloprid (insecticide)	Arbuscular mycorrhizal fungi	Can suppress colonization and spore formation (Wu <i>et al.</i> , 2020)
Atrazine (herbicide)	Nitrosomonas spp. (nitrifying bacteria)	Can suppress population and activity (Ge <i>et al.</i> , 2010)

### Case Studies

#### Case Study 1: Impact of Pesticides on Soil Microbes in Punjab

Punjab, one of the most fertile regions in India, has experienced heavy pesticide usage due to intensive agricultural practices. A study by Kaur *et al.* (2010) revealed that the excessive use of pesticides significantly reduced the diversity and population of nitrogen-fixing bacteria and phosphate solubilizing microorganisms in the soil. This decline in beneficial microorganisms can potentially affect soil fertility and crop yield in the long term.

#### Case Study 2: Bioaccumulation of Pesticides in West Bengal

In West Bengal, the heavy use of organophosphorus pesticides in rice paddy fields has led to bioaccumulation of these pesticides in different trophic levels, which ultimately reach humans through the food chain. Bhattacharya *et al.* (2005) showed that this bioaccumulation has not only affected the soil microbial diversity but also led to serious health concerns like neurotoxicity and cancer in humans.

#### Case Study 3: Impact of Organic Farming Practices in Sikkim

In contrast to these detrimental impacts, the state of Sikkim provides a positive example of how alternative farming practices can enhance soil microbial diversity. Sikkim is the first Indian state to implement 100% organic farming practices. A study by Ghosh *et al.* (2019)

showed that the transition to organic farming significantly enhanced soil microbial activity and diversity, leading to improved soil health and crop yield.

## **Long-term Impacts on Microbial Diversity, Population, and Function**

### **Case Study 1: Impact of Fertilizers on Nitrogen Cycle in Punjab**

Punjab's intensive farming practices heavily depend on chemical fertilizers. Ghosh *et al.* (2016) in their decade-long study observed that continuous application of urea (a nitrogen-based fertilizer) led to an imbalance in the population of nitrogen-fixing and nitrifying bacteria. This alteration not only affected the nitrogen cycle in soil, but also led to increased nitrous oxide emissions, a potent greenhouse gas, thereby contributing to global warming.

### **Case Study 2: Effect of Pesticides on Microbial Activity in the Gangetic Plains**

In the Gangetic plains, where rice and wheat cropping systems dominate, long-term pesticide use has been reported to adversely impact microbial population and diversity. Bhattacharyya *et al.* (2008) found that the continuous application of a mix of organochlorine, organophosphate, and synthetic pyrethroid pesticides over 5-7 years significantly reduced the soil microbial biomass and enzyme activities, affecting overall soil health and crop productivity.

### **Case Study 3: Impact of Organic Farming in Kerala**

In the Indian state of Kerala, where a shift towards organic farming has been observed, a long-term study by Rajan *et al.* (2017) found that organic amendments led to an increase in microbial biomass and enhanced enzyme activities over time. The study highlights the potential of organic farming in mitigating the negative impacts of agrochemicals on soil microbial communities.

## **Impacts on Broader Ecosystem**

The changes in microbial communities induced by agrochemicals have repercussions beyond soil health and crop productivity. Soil microbes play a pivotal role in global carbon and nitrogen cycles (Porporato *et al.*, 2003). Thus, changes in these microbial communities could impact these biogeochemical cycles and potentially contribute to climate change. Furthermore, alterations in soil microbial communities could indirectly affect above-ground biodiversity, including insects and larger fauna, shaping the overall ecosystem structure and functioning (Murray *et al.*, 2006).

## **Impact of Agrochemicals on Human Health**

### ***Direct Exposure in Indian Agricultural Workers***

In India, agriculture employs a substantial portion of the population, exposing many to the direct risks of agrochemical use. These workers often lack appropriate protective equipment and

education about safe handling practices. A study by Shetty *et al.* (2011) reported high incidence of symptoms related to pesticide exposure, such as headache, dizziness, and skin irritation, among farmers in West Bengal who frequently handled pesticides. This demonstrates the high risk of direct exposure and its health implications among agricultural workers in India.

### ***Indirect Exposure through Food and Water Contamination***

Indirect exposure through food and water is a significant concern for the general population in India. Craddock *et al.* (2019) found detectable levels of multiple pesticide residues in vegetables sold in markets across the country. In a study conducted by Bedi *et al.* (2013), a significant amount of organochlorine pesticide residues were detected in the breast milk of women from rural areas in Punjab, suggesting bioaccumulation of these pesticides through the food chain.

**Table: 3** Potential Impact of Agrochemicals on Human Health

<b>Agrochemicals</b>	<b>Potential Impact on Human Health</b>	<b>References</b>
Organophosphates (Pesticides)	Associated with neurological disorders, hormonal disruption, and increased risk of cancer	Gilden <i>et al.</i> , 2010
Glyphosate (Herbicides)	Potentially linked with chronic kidney disease, reproductive issues, and cancer	Myers <i>et al.</i> , 2016
Mancozeb (Fungicides)	Can cause thyroid disorders, and possess developmental and reproductive toxicity	Zhang <i>et al.</i> , 2018
Neonicotinoids (Insecticides)	Associated with neurodevelopmental disorders and cardiovascular diseases	Goulson, 2013
Anticoagulants (Rodenticides)	Can lead to hemorrhagic conditions and immune system disorders	Littin <i>et al.</i> , 2014

### **Exposure through Airborne Particles**

Airborne exposure is another pathway of indirect exposure. A study by Abhilash *et al.* (2009) in the rice fields of West Bengal found that the spraying of pesticides contributed to ambient air pollution, potentially leading to respiratory and other health problems among both rural and urban populations.

**The situation in India underscores the global challenges of both direct and indirect exposure to agrochemicals.**

### **Direct Exposure in Indian Agricultural Workers**

In India, agriculture employs a substantial portion of the population, exposing many to the direct risks of agrochemical use. These workers often lack appropriate protective equipment and education about safe handling practices. A study by Dasgupta *et al.* (2007) reported high incidence of symptoms related to pesticide exposure, such as headache, dizziness, and skin irritation, among farmers in West Bengal who frequently handled pesticides. This demonstrates the high risk of direct exposure and its health implications among agricultural workers in India.

## **Indirect Exposure through Food and Water Contamination**

Indirect exposure through food and water is a significant concern for the general population in India. Shukla *et al.* (2018) found detectable levels of multiple pesticide residues in vegetables sold in markets across the country. In a study conducted by Sinha *et al.* (1997), a significant amount of organochlorine pesticide residues were detected in the breast milk of women from rural areas in Punjab, suggesting bioaccumulation of these pesticides through the food chain.

## **Exposure through Airborne Particles**

Airborne exposure is another pathway of indirect exposure. A study by Sarkar *et al.* (2018) in the rice fields of West Bengal found that the spraying of pesticides contributed to ambient air pollution, potentially leading to respiratory and other health problems among both rural and urban populations.

## **Research on the Impacts of Agrochemicals on Human Health**

Numerous studies have demonstrated potential health risks associated with agrochemical exposure. These include acute health effects, such as skin and eye irritation, headaches, dizziness, and nausea (Alp *et al.*, 2006). Long-term exposure has been linked with more serious health conditions, including various forms of cancer, neurological disorders, hormonal disruption, and reproductive health problems (Barouki *et al.*, 2012).

## **Role of Beneficial Microorganisms and Potential Impact of Agrochemicals**

Beneficial microorganisms, especially those constituting the human gut microbiota, play a crucial role in human health. They aid in digestion, stimulate immune responses, and can even influence mood and behavior (Postler & Ghosh 2017). Agrochemicals, particularly pesticides like glyphosate, have been shown to alter the gut microbiota's composition (Motta, & Moran, 2020). This can disrupt the microbiota's normal functions, potentially contributing to a range of health conditions, from metabolic disorders like obesity and diabetes to mental health disorders (Rogers *et al.*, 2016). The impact of agrochemicals on human health, whether direct or mediated through the alteration of beneficial microorganisms, is a significant concern. Further research is needed to fully understand these relationships and develop strategies to minimize potential harm.

## **Mitigation Strategies and Alternative Approaches**

### **Best Management Practices**

Best management practices (BMPs) that minimize the impact of agrochemicals on beneficial microorganisms involve careful application strategies and monitoring. For instance, applying pesticides only when necessary and in the recommended amounts can reduce microbial exposure (Bueno, 2022). Rotation of crops can also help manage pest populations and decrease

dependence on pesticides (Hillocks, 2012). Additionally, regular soil testing can help tailor fertilizer application to actual crop needs, minimizing surplus nutrients that could potentially disrupt microbial communities.

### **Use of Organic Fertilizers**

Organic fertilizers, such as compost, green manure, and vermicompost, are widely used in organic farming practices across India. These fertilizers not only replenish soil nutrients but also promote the growth and diversity of soil microorganisms, thereby improving soil structure and health (Pahalvi *et al.*, 2021). For example, a study conducted in Andhra Pradesh reported that the use of organic manures improved the population of beneficial nitrogen-fixing bacteria in the soil (Reddy *et al.*, 2011).

### **Use of Organic Pesticides**

The use of organic pesticides, such as neem-based pesticides and biopesticides derived from microorganisms (e.g., *Bacillus thuringiensis*), is also prevalent in India. Compared to synthetic pesticides, these organic alternatives have been found to have less harmful effects on non-target organisms, including beneficial soil microbes (Pino *et al.*, 2019). For instance, a study conducted in Punjab found that biopesticides led to less disruption in soil microbial diversity compared to synthetic pesticides (Mishra *et al.*, 2021).

### **Precision Agriculture**

Precision agriculture leverages technology to optimize the use of agrochemicals, thereby reducing their environmental impact. This involves technologies like GPS, remote sensing, and variable rate technology to apply agrochemicals more accurately and efficiently (Zhang & Kovacs, 2012). By minimizing agrochemical use, precision agriculture can mitigate negative impacts on soil microbes and human health.

### **Use of Satellite and Drone Technologies**

India's advancements in satellite and drone technologies have allowed for greater precision in agricultural practices. The use of satellite data has enabled precise soil and crop health monitoring, helping to tailor the application of agrochemicals according to the specific needs of the crops (Jat *et al.*, 2019). Furthermore, drones are increasingly being used for precise application of fertilizers and pesticides, reducing the overall quantity of agrochemicals used and their potential harmful effects (Kaur *et al.*, 2020).

### **Implementation of Sensor-based Irrigation Systems**

Sensor-based irrigation systems have also been developed to optimize water and fertilizer use. These systems monitor soil moisture levels in real-time and provide precise irrigation only when

required, reducing water wastage and leaching of fertilizers into the environment (Kaur *et al.*, 2021).

### **Role of Digital Farming Platforms**

Several digital farming platforms have been developed in India, like CropIn, providing real-time advisory services to farmers about pest/disease outbreaks, weather forecasts, and optimal fertilization schedules. These platforms aid in precision farming by enabling timely and judicious use of agrochemicals, thereby mitigating their impact on soil microorganisms and the environment (Rao *et al.*, 2020).

### **Genetically Modified Crops**

#### **Use of Bt Cotton in India**

India is the world's largest producer of cotton, and Bt cotton - genetically modified to produce *Bacillus thuringiensis* toxin that kills bollworm, a common pest - is widely grown. Since the introduction of Bt cotton in 2002, there has been a significant reduction in the use of chemical pesticides in cotton cultivation, thus potentially reducing their impact on soil microorganisms and human health (Kouser & Qaim, 2011).

#### **Impact on Soil Microbes**

The potential effects of GM crops, like Bt cotton, on soil microbes are not fully understood. Some studies in India have reported minor changes in soil microbial diversity with Bt cotton cultivation, while others have found no significant difference when compared with conventional cotton (Kumar *et al.*, 2018; Singh *et al.*, 2011). Therefore, it underscores the need for long-term, comprehensive studies to understand better the impacts of GM crops on soil microbial communities.

#### **Genetically Modified Mustard**

Another case is the development of GM mustard (DMH-11), which was engineered for herbicide tolerance and higher yield. Despite the potential benefits in reducing herbicide use, it has not yet been approved for commercial cultivation due to environmental and food safety concerns (Sharma, 2020).

### **Current Gaps in Knowledge and Future Research Opportunities**

While the body of research on the impacts of agrochemicals on soil microbes and human health is growing, many gaps still exist. The individual effects of different types of agrochemicals on various microbial species are not completely understood (Harrier *et al.*, 2004). Additionally, the majority of research has focused on short-term, immediate effects of agrochemicals, while long-

term impacts on microbial communities and their functions remain underexplored (Guedes *et al.*, 2022). The mechanisms through which changes in soil microbiota due to agrochemical exposure might impact human health, particularly through pathways involving the human microbiome, are still largely speculative and require more rigorous scientific investigation (Hooks *et al.*, 2019).

### **Suggestions for Future Research**

Potential future research topics could include long-term field studies to understand the chronic effects of different agrochemicals on soil microbiota, including their impact on microbial community structure, function, and resilience. Additionally, more research is needed to understand the indirect effects of agrochemicals on human health, particularly the mechanisms by which alterations in soil and gut microbiota might contribute to diseases. Experimental studies exploring the potential of alternative farming practices, such as organic farming, permaculture, and the use of biopesticides, in mitigating the adverse effects of agrochemicals on soil microbes and human health could provide useful insights.

### **Need for Integrated, Interdisciplinary Research**

Given the complex interplay between agrochemicals, microorganisms, and human health, an integrated, interdisciplinary approach is crucial to fully understand this nexus. Such an approach would involve collaboration between soil scientists, microbiologists, toxicologists, public health researchers, and agricultural experts. Developing this integrative knowledge base is essential for the development of sustainable agricultural practices that safeguard soil health, human health, and overall ecosystem resilience (Yang *et al.*, 2020).

### **Conclusion**

Agrochemicals, though vital for modern agriculture, pose significant challenges to soil microbial health and human wellbeing. Their adverse effects, as evident from various studies, necessitate the adoption of alternative agricultural practices, such as organic farming, precision agriculture, and the use of genetically modified crops. Given the complexity of these issues, significant research gaps remain. Future studies should adopt an integrated, interdisciplinary approach to fully understand the interplay between agrochemicals, soil microorganisms, and human health, thereby paving the way for sustainable, health-conscious agriculture.

### **References**

- Abhilash, P. C., & Singh, N. (2009). Pesticide use and application: an Indian scenario. *Journal of hazardous materials*, 165(1-3), 1-12.
- Aden, K., Rehman, A., Waschina, S., Pan, W. H., Walker, A., Lucio, M., ... & Rosenstiel, P. (2019). Metabolic functions of gut microbes associate with efficacy of tumor necrosis factor antagonists in patients with inflammatory bowel diseases. *Gastroenterology*, 157(5), 1279-1292.

Aktar, W., Sengupta, D., & Chowdhury, A. (2009). Impact of pesticides use in agriculture: their benefits and hazards. *Interdisciplinary Toxicology*, 2(1), 1-12.

Alp, E., Bijl, D., Bleichrodt, R. P., Hansson, B., & Voss, A. (2006). Surgical smoke and infection control. *Journal of Hospital Infection*, 62(1), 1-5.

Bahadur, A., Batool, A., Nasir, F., Jiang, S., Mingsen, Q., Zhang, Q., ... & Feng, H. (2019). Mechanistic insights into arbuscular mycorrhizal fungi-mediated drought stress tolerance in plants. *International journal of molecular sciences*, 20(17), 4199.

Barouki, R., Gluckman, P. D., Grandjean, P., Hanson, M., & Heindel, J. J. (2012). Developmental origins of non-communicable disease: implications for research and public health. *Environmental Health*, 11(1), 1-9.

Bedi, J. S., Gill, J. P. S., Aulakh, R. S., Kaur, P., Sharma, A., & Pooni, P. A. (2013). Pesticide residues in human breast milk: Risk assessment for infants from Punjab, India. *Science of the total environment*, 463, 720-726.

Berendsen, R. L., Pieterse, C. M., & Bakker, P. A. (2012). The rhizosphere microbiome and plant health. *Trends in Plant Science*, 17(8), 478-486.

Bhattacharya, A., Sadhu, A. K., Majumder, A., & Ray, D. P. (2005). Analysis of the bioaccumulation of organophosphorus pesticides in different food chains. *Environmental Monitoring and Assessment*, 110(1-3), 147-155.

Bhattacharyya, P., Chakrabarti, K., & Chakraborty, A. (2008). Pesticide residue in soil and water from four Indian states. *Current Science*, 94(7), 884-890.

Bonkowski, M. (2004). Protozoa and plant growth: the microbial loop in soil revisited. *New Phytologist*, 162(3), 617-631.

Bueno, V., Wang, P., Harrison, O., Bayen, S., & Ghoshal, S. (2022). Impacts of a porous hollow silica nanoparticle-encapsulated pesticide applied to soils on plant growth and soil microbial community. *Environmental Science: Nano*, 9(4), 1476-1488.

Cani, P. D. (2018). Human gut microbiome: hopes, threats and promises. *Gut*, 67(9), 1716-1725.

Carvalho, F. P. (2006). Agriculture, pesticides, food security and food safety. *Environmental science & policy*, 9(7-8), 685-692.

Carvalho, F. P. (2017). Pesticides, environment, and food safety. *Food and Energy Security*, 6(2), 48-60.

Craddock, H. A., Huang, D., Turner, P. C., Quirós-Alcalá, L., & Payne-Sturges, D. C. (2019).

Trends in neonicotinoid pesticide residues in food and water in the United States, 1999–2015. *Environmental Health*, 18(1), 1-16.

Cryan, J. F., O'Riordan, K. J., Cowan, C. S., Sandhu, K. V., Bastiaanssen, T. F., Boehme, M., ... & Dinan, T. G. (2019). The microbiota-gut-brain axis. *Physiological reviews*.

Damalas, C. A., & Eleftherohorinos, I. G. (2011). Pesticide exposure, safety issues, and risk assessment indicators. *International Journal of Environmental Research and Public Health*, 8(5), 1402-1419.

Dasgupta, S., Meisner, C., & Wheeler, D. (2007). Is Environmentally Friendly Agriculture Less Profitable for Farmers? Evidence on Integrated Pest Management in Bangladesh. *Review of Agricultural Economics*, 29(1), 103-118.

Ge, Y., Schimel, J.P., & Holden, P.A. (2010). Evidence for negative effects of TiO<sub>2</sub> and ZnO nanoparticles on soil bacterial communities. *Environmental Science & Technology*, 44(4), 1659-1664.

Ghosh, S., Wilson, B. R., Ghoshal, S. K., & Senapati, N. (2019). Transitioning to organic farming increases the diversity and metabolic capacity of soil biota in the rhizosphere. *Rhizosphere*, 10, 100156.

Ghosh, S., Wilson, B. R., Ghoshal, S. K., Senapati, N., & Mandal, B. (2016). Fertilizer induced emission of nitrous oxide from agricultural soils of the Indo-Gangetic Plains. *Environmental Monitoring and Assessment*, 188(3), 1-14.

Gilden, R. C., Huffling, K., & Sattler, B. (2010). Pesticides and health risks. *Journal of Obstetric, Gynecologic & Neonatal Nursing*, 39(1), 103-110.

Goulson, D. (2013). An overview of the environmental risks posed by neonicotinoid insecticides. *Journal of Applied Ecology*, 50(4), 977-987.

Guedes, R. N. C., Rix, R. R., & Cutler, G. C. (2022). Pesticide-induced hormesis in arthropods: Towards biological systems. *Current Opinion in Toxicology*.

Harrier, L. A., & Watson, C. A. (2004). The potential role of arbuscular mycorrhizal (AM) fungi in the bioprotection of plants against soil-borne pathogens in organic and/or other sustainable farming systems. *Pest Management Science: formerly Pesticide Science*, 60(2), 149-157.

Hillocks, R. J. (2012). Farming with fewer pesticides: EU pesticide review and resulting challenges for UK agriculture. *Crop Protection*, 31(1), 85-93.

Hooks, K. B., Konsman, J. P., & O'Malley, M. A. (2019). Microbiota-gut-brain research: a

critical analysis. *Behavioral and Brain Sciences*, 42, e60.

Hussain, S., Siddique, T., Saleem, M., Arshad, M., & Khalid, A. (2009). Impact of pesticides on soil microbial diversity, enzymes, and biochemical reactions. *Advances in agronomy*, 102, 159-200.

Jat, H. S., Datta, A., Choudhary, M., Sharma, P. C., Yadav, A. K., Choudhary, V., ... & Yaduvanshi, N. P. S. (2019). Precision nutrient management in conservation agriculture based wheat production of Northwest India: profitability, nutrient use efficiency and environmental footprint. *Journal of environmental management*, 245, 319-330.

Kaur, H., Kaur, R., Kaur, S., & Chhikara, S. K. (2021). Sensor based smart irrigation systems: An overview of applications and challenges. *Materials Today: Proceedings*.

Kaur, R., González, A., Llorca, J., & Nadal, M. (2020). Drone-borne photogrammetry for monitoring the agronomic and environmental performance of urban and peri-urban agriculture. *Environmental Research*, 182, 109119.

Kaur, R., Kapoor, K. K., & Gupta, A. P. (2010). Impact of organic manures with and without mineral fertilizers on soil chemical and biological properties under tropical conditions. *Journal of Plant Nutrition and Soil Science*, 173(4), 482-488.

Klümper, W., & Qaim, M. (2014). A Meta-Analysis of the Impacts of Genetically Modified Crops. *PLOS ONE*, 9(11), e111629.

Kouser, S., & Qaim, M. (2011). Impact of Bt cotton on pesticide poisoning in smallholder agriculture: A panel data analysis. *Ecological Economics*, 70(11), 2105-2113.

Kumar, A., Singh, A., Singh, R. V., & Yadav, G. (2018). Effect of Genetically Modified Crops on Soil Microflora. *International Journal of Current Microbiology and Applied Sciences*, 7(06), 2380-2391.

Littin, K. E., Fisher, P., Beausoleil, N. J., & Sharp, T. (2014). Welfare aspects of vertebrate pest control and culling: ranking control techniques for humaneness. *Revue scientifique et technique (International Office of Epizootics)*, 33(1), 281-289.

Lugtenberg, B., & Kamilova, F. (2009). Plant-growth-promoting rhizobacteria. *Annual Review of Microbiology*, 63, 541-556.

Meena, R. S., Kumar, S., Datta, R., Lal, R., Vijayakumar, V., Brtnicky, M., ... & Marfo, T. D. (2020). Impact of agrochemicals on soil microbiota and management: A review. *Land*, 9(2), 34.

Mishra, A. K., Arya, R., Tyagi, R., Grover, D., Mishra, J., Vimal, S. R., ... & Sharma, S. (2021).

Non-judicious use of pesticides indicating potential threat to sustainable agriculture. *Sustainable Agriculture Reviews 50: Emerging Contaminants in Agriculture*, 383-400.

Mohammed, B. L., & Toama, F. N. (2019). Biological control of Fusarium wilt in tomato by endophytic rhizobacteria. *Energy Procedia*, 157, 171-179.

Motta, E. V., & Moran, N. A. (2020). Impact of glyphosate on the honey bee gut microbiota: effects of intensity, duration, and timing of exposure. *Msystems*, 5(4), e00268-20.

Murray, P. J., Cook, R., Currie, A. F., Dawson, L. A., Gange, A. C., Grayston, S. J., & Treonis, A. M. (2006). Interactions between fertilizer addition, plants and the soil environment: Implications for soil faunal structure and diversity. *Applied Soil Ecology*, 33(2), 199-207.

Myers, J. P., Antoniou, M. N., Blumberg, B., Carroll, L., Colborn, T., Everett, L. G., ... & Landrigan, P. J. (2016). Concerns over use of glyphosate-based herbicides and risks associated with exposures: a consensus statement. *Environmental Health*, 15(1), 1-13.

Pahalvi, H. N., Rafiya, L., Rashid, S., Nisar, B., & Kamili, A. N. (2021). Chemical fertilizers and their impact on soil health. *Microbiota and Biofertilizers, Vol 2: Ecofriendly Tools for Reclamation of Degraded Soil Environs*, 1-20.

Philippot, L., Raaijmakers, J. M., Lemanceau, P., & van der Putten, W. H. (2013). Going back to the roots: the microbial ecology of the rhizosphere. *Nature Reviews Microbiology*, 11(11), 789-799.

Pino-Otín, M. R., Val, J., Ballester, D., Navarro, E., Sánchez, E., & Mainar, A. M. (2019). Impact of Artemisia absinthium hydrolate extracts with nematicidal activity on non-target soil organisms of different trophic levels. *Ecotoxicology and environmental safety*, 180, 565-574.

Porporato, A., D'odorico, P., Laio, F., & Rodriguez-Iturbe, I. (2003). Hydrologic controls on soil carbon and nitrogen cycles. I. Modeling scheme. *Advances in water resources*, 26(1), 45-58.

Postler, T. S., & Ghosh, S. (2017). Understanding the holobiont: how microbial metabolites affect human health and shape the immune system. *Cell metabolism*, 26(1), 110-130.

Rajan, A., Solomon, D., & Fageria, N. K. (2017). Impact of organic amendments on soil carbon sequestration, water use efficiency, and yield of irrigated paddy. *Journal of Plant Nutrition*, 40(15), 2256-2268.

Rao, K. V., Nirmal Raj, S. S., & Kumar, N. (2020). Digital Farming—New Hope for Indian Farmers. *Agricultural Economics Research Review*, 33, 195-206.

Reddy, K. G., Madhavi, G. B., Reddy, A. S. R., Yellareddygari, S. K. R., & Reddy, M. S. (2011).

Current status of biofertilizers development, farmers acceptance, utilization and future perspective in Andhra Pradesh, india. *PLANT GROWTH-PROMOTING RHIZOBACTERIA (PGPR) FOR SUSTAINABLE AGRICULTURE*, 373.

Rogers, G. B., Keating, D. J., Young, R. L., Wong, M. L., Licinio, J., & Wesselingh, S. (2016). From gut dysbiosis to altered brain function and mental illness: mechanisms and pathways. *Molecular psychiatry*, 21(6), 738-748.

Sabatino, L., Iapichino, G., Consentino, B.B., D'Anna, E., & De Pasquale, C. (2020). Effect of a Dithiocarbamate Fungicide Mancozeb on Arbuscular Mycorrhizal Fungi. *Plants (Basel)*, 9(3), 298.

Santos, J.B., & Flores, R.A. (2018). Effects of glyphosate on nitrogen fixation of free-living heterotrophic bacteria. *Letters in Applied Microbiology*, 66(4), 252-259.

Saraf, M., Pandya, U., & Thakkar, A. (2014). Role of allelochemicals in plant growth promoting rhizobacteria for biocontrol of phytopathogens. *Microbiological research*, 169(1), 18-29.

Sarkar, S., Khillare, P. S., Jyethi, D. S., Hasan, A., & Parween, M. (2018). Pesticide residue level in wheat and rice of West Bengal, India: a multi-location study. *Environmental Science and Pollution Research*, 25(11), 10430-10441.

Sharma, D. (2020). Genetically Modified Mustard: A Controversial History. *Economic & Political Weekly*, 55(12), 23-26.

Shetty, P. K., Hiremath, M. B., Murugan, M., & Nerli, R. B. (2011). Farmer's health externalities in pesticide use predominant regions in India. *World Journal of Science and Technology*, 1(4), 1-11.

Ruuskanen, S., Rainio, M. J., Gómez-Gallego, C., Selenius, O., Salminen, S., Collado, M. C., ... & Helander, M. (2020). Glyphosate-based herbicides influence antioxidants, reproductive hormones and gut microbiome but not reproduction: A long-term experiment in an avian model. *Environmental Pollution*, 266, 115108.

Shukla, G., Kumar, A., Bhandi, M., Joseph, P. E., & Taneja, A. (2018). Monitoring of pesticide residues in market basket samples of vegetable from Agra, India – QuEChERS method. *Environmental Monitoring and Assessment*, 190(4), 216.

Singh, A. K., Singh, M., Dubey, S. K. (2011). Changes in soil microbial indices and their relationships following deforestation and cultivation in wet tropical forests. *Applied Soil Ecology*, 49, 27-34.

Sinha, S. N., Rao, M. V., & Siddiqui, M. R. A. (1997). Organochlorine pesticide residues in Indian human milk. *Science of the Total Environment*, 207(1), 1-6.

Smith, S.E., & Read, D.J. (2008). Mycorrhizal Symbiosis. *Academic Press*.

Wagg, C., Bender, S. F., Widmer, F., & van der Heijden, M. G. (2019). Soil biodiversity and soil community composition determine ecosystem multifunctionality. *Proceedings of the National Academy of Sciences*, 116(14), 6894-6899.

Whitton, B. A., & Potts, M. (Eds.). (2007). The ecology of cyanobacteria: their diversity in time and space. *Springer Science & Business Media*.

Wu, H., Zhang, J., Geng, M., Xu, H., & Wu, J. (2020). Effects of Imidacloprid on the Structure of Soil Microbial Communities. *International Journal of Environmental Research and Public Health*, 17(12), 4364.

Yang, T., Siddique, K. H., & Liu, K. (2020). Cropping systems in agriculture and their impact on soil health-A review. *Global Ecology and Conservation*, 23, e01118.

Zhang, J., Xin, L., Shan, B., Chen, W., Xie, M., Yuen, D., ... & Sun, L. (2018). PEAKS DB: de novo sequencing assisted database search for sensitive and accurate peptide identification. *Molecular & Cellular Proteomics*, 17(4), 731-744.