International Journal of Chemical and Biochemical Sciences
(ISSN 2226-9614)

Journal Home page: www.iscientific.org/Journal.html

Environmental, Microbiological and Chemical Implications of Fertilizers use in soils: A review

Faiqa Amin*[1], Muhammad Idrees Jilani[2]

[1]Department of Chemistry, University of Agriculture, Faisalabad-38040-Pakistan.

[2]Department of Chemistry, The University of Lahore, Lahore, Pakistan

Abstract

In developing countries, the most significant factor affecting economic growth is sustainable agriculture. The Green Revolution helped developing nations to reduce their persistent food shortages by increasing food. Fertilizers are the primary nutrient source to keep the soil fertile. But due to the deficiency or overuse of conventional fertilizers, many adverse environmental, microbiological, and chemical effects may occur. The effects on the environment include nitrate leaching, eutrophication, soil acidification, pollution of ground and surface water, increased levels of greenhouse gas emissions, thinning of the ozone layer, global warming, and even biodiversity losses. Beneficial microorganisms for agriculture can also enhance crops and boost fertilizer efficacy. However, prolonged applications of chemical fertilizers may alter the composition of the microbial community and biogeochemical cycles. Application of excessive fertilizer in croplands can be a significant source of potentially harmful heavy metals like arsenic, cadmium, and lead in the soil. To achieve sustainability in the modern agriculture sector, nanotechnology must be used during the manufacturing of environmentally friendly fertilizers (EFFs), as they not only increase crop yield and soil fertility but also mitigate major environmental issues by regulating the release of nutrients. Even by utilizing organic methods, some environmental problems may be eliminated. This review aims to cover all the positive impacts of fertilizers and their detrimental effects on the environment, microbiological and chemical systems, along with possible solutions.

Keywords: conventional fertilizers; environmental pollution; eutrophication; microbiological effects; biogeochemical cycle; EFFs

Full length review article **Corresponding Author*, e-mail: fjutt3598@gmail.com

1. Introduction

One of the main challenges in implementing sustainable approaches is raising food production to meet the demands of the world's expanding population. The population is continuing to expand and has reached 7.37 billion [1]. Application of fertilizers containing nitrogen has led to increased crop output, which has supported the lives of people that live on the planet [2]. So, the global economy greatly depends on fertilizers [3]. Farmers need to replenish the nutrients in the soil in order to keep it fertile, as with synthetic or natural fertilizers. This process improves sustainability, conserves resources, and also has economic and environmental benefits [4-5]. Chemical fertilizers, also referred to as mineral, inorganic, or synthetic fertilizers, are composed of inorganic salts that are primary nutrients (nitrogen, N; potassium, K; phosphorous, P). Chemical fertilizers can also add sulfur, magnesium, and calcium, which are secondary elements. The level of nutrients in chemical fertilizers is denoted by the N:P:K level, which shows the total amount of nitrogen, phosphorus and potassium. Remarkable increases in agricultural yield that have been achieved since the 1950s can be largely attributed to mineral fertilizers, particularly nitrogen (N) inputs [6], and worldwide use of fertilizer in graphical form in figure 1 [7]. N fertilizers are primarily applied in ammonium (NH_4^+) and nitrate (NO_3^-) forms [8-9]. In modern day agriculture, nitrogen fertilizers are frequently utilized to preserve soil fertility and yield [10]. For soil fertility to be maintained, both organic and inorganic fertilizers must be used together [11-13]. Lack of nutrients, a low environment and poor soil quality suffer from the uneven use of synthetic fertilizers. However, bacterial diversity and enzyme activity are greatly influenced by fertilizers [14-15].

Adverse impacts of chemical fertilizers on the environment are growing day by day. Indeed, they have the potential to significantly increase emissions of greenhouse gases and contaminate ecosystems. For instance, it has been found that the primary cause of the direct release of nitrogen dioxide into the atmosphere is the biodegradation of synthetic nitrogen fertilizers by soil microorganisms [9-16].

Furthermore, synthetic nitrogen fertilizers have a high dissolution rate, only about 50–60% of fertilizer is typically absorbed by crops, and the remainder flows off into surface or groundwater [17]. Heavy metals and soil eutrophication can result from the overuse of phosphorus fertilizers [9-10]. The chemical, physical, and microbiological qualities of soil can all be altered by fertilizers. Yet, as microorganism diversity and soil health indicators are vital to soil quality and nutrient metabolism but unbalanced fertilizer application can have a detrimental impact on these elements [9]. Nearly fifty percent of the nitrogen fertilizer used is dispersed to the environment via volatilization, drainage, or leaching and is not utilized by crops [18]. These impairments result in environmental issues like greenhouse gas emissions, water body pollution, acidification of the ground, or a decline in biodiversity [19].

The vast diversity of organisms that make up soil biota includes microorganisms like bacteria, and fungi which constitute the most significant variety of soil organisms [20]. In addition to enhancing soil structure, they can act as a beneficial source of soil microbes [21]. Microbes found in soil have a substantial effect on major processes like the cycles of carbon, phosphorous, and nitrogen. For instance, microorganisms are responsible for the ecological processes of nitrogen fixation, ammonia oxidation, denitrification, and ammonification [22]. In general, beneficial rhizosphere microbes can promote plant growth through a large number of regulatory biochemical routes, like regulating plant hormone signaling and enhancing the absorption of nutrients found in soil [23-26]. Nitrosomonas and Nitrobacter, two types of nitrogen-fixing bacteria found in soil, carry out the conversion of nitrogen, which is also referred to as nitrification or nitrogen fixation [27]. Ammonium (NH_4^+) and nitrate (NO_3^-) are active chemical forms of N that are accessible for biosynthesis [19]. On the other hand, leaching and denitrification may cause a loss of nitrogen and pollution of the environment. Soil health is also affected by numerous variables, such as the amount of nutrients, type of soil, and management techniques [28]. Variations in the environment that affect the microbial communities in soil may have an adverse effect on the relationship between microorganisms and plants [9]. Under certain circumstances, the soluble fertilizer may release itself uncontrollably into the area around the plant, resulting in leaching and modifications of microbiological composition that could have a detrimental effect [29-32].

Appropriate application of chemical fertilizers can accelerate agricultural productivity. Conversely, overuse can have negative impacts on the environment, including pollution of soil and water, soil pH, and airborne NO_2 emissions [33]. Heavy metals like cadmium (Cd), arsenic (As), mercury (Hg), nickel (Ni), lead (Pb), and copper (Cu) can be found in chemical fertilizers [34]. Furthermore, excessive use of chemical fertilizers raises soil acidity and decreases the quantity of organic matter in the soil [35]. Extended usage of chemical fertilizers hardens the soil, loses its fertility, and reduces vital minerals and soil nutrients, all of which pose environmental risks [36]. Because of the accumulation of heavy metals in soil, the threat of environmental pollution has been rising quickly recently [37-38]. Thus, maintaining agricultural productivity while minimizing the harmful effects of fertilizers on the environment is challenging [39]. Reducing chemical fertilizers and pesticides would also help to maintain the biogeochemical cycle of soil and enhance soil health, both of which improve crop production [1]. During the past few decades, the use of nanotechnology to food production, agriculture, and the reduction of environmental problems has been highly favorable [40].

2. Types and effects of fertilizers

Fertilizer is a chemical mixture of different necessary minerals and elements intended to give regular and accelerated growth and nourishment to all plants [41]. Fertilizers enhance soil fertility and nutrient status by providing deficient chemicals. Plant cells require nitrogen, phosphorous, and potassium for their proper functioning. The main element that controls plant growth and yield is the availability of nutrients [42]. For maximum growth and productivity, plants primarily require 17 nutrients, which are primarily composed of four major elements: hydrogen, oxygen, carbon, and nitrogen [43-44]. But their overuse has hazardous effects on nature.

2.1: *Organic fertilizers*

Sources of organic fertilizers are living and biodegradable substances. They decomposed complex substances into simpler ones by microorganisms [41]. They enhanced the texture, moisture retention, and erosion resistance of the soil, but they released nutrients slowly. Utilizable nutrients are provided by organic fertilizers, assisting plants in growing more vigorously. But temperature and water content have a significant impact on organic matter decomposition, so when plants do not need nutrients, they might release them. However, these fertilizers are considered to be safe for the environment [45]. Different natural and synthetic sources of organic fertilizers are represented in figure 2 [41].

2.2: Inorganic fertilizers

Inorganic fertilizers are manufactured by inorganic or chemical substances [41]. They release nutrients quickly, so help in plant growth and productivity. Besides these advantages, there are a lot of disadvantages to inorganic fertilizers, as the fact they cause environmental and water pollution, soil erosion, and degradation. Different types of inorganic fertilizers with examples, are described in Table 1 [45].

2.3: Macronutrients and Micronutrients Fertilizers

Plant accessibility to nutrients is often impacted by the addition of fertilizers containing macronutrients. Plant macronutrients are supplied by numerous fertilizers [46]. Nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur are vital plant macronutrients [46-47].The three main macronutrients are found in fertilizers containing NPK [47-48]. The primary factor affecting crop yield is deficiency in vital nutrients, specifically phosphorus (P) and nitrogen (N) [49-50]. A nutrient called nitrogen is vital for the proper development of living things [51]. NO_3^- and NO_2^-, both of which are the main forms in nitrogen fertilizers [52]. Phosphorus is an essential nutrient for plant growth [53-54].

Mineral fertilizers meet between fifty to sixty percent of the world's phosphorus-based fertilizer needs [55]. Additionally, plants require a few key nutrients in tiny but crucial amounts; their growth may be greatly hindered in their absence. The purpose of micronutrient fertilizers is to meet the vital requirements of plants [41]. In general, micronutrient availability increases when the pH of the soil falls below 7 [46]. Classification of plant nutrients in air, soil, and water is depicted in figure 3 [56].

3. Impact of Fertilizers on the Environment

For the past few years, agricultural fields have been continuously treated with chemical pesticides and fertilizers, which has increased agricultural yield and chemical fertilizer consumption. The modern era requires that all environmental components be kept in balance in order to support sustainable living. However, a number of chemical reactions in industries are affecting different species, which causes instability in biodiversity [7]. Environmental components are significantly impacted by fertilizers. One important element that causes detrimental effects on the environment is inefficient fertilizer uptake [57]. Research revealed that high fertilizer use shows negative effects on human toxicity, soil acidification, depletion of ozone in the stratosphere, and a risk for global warming [3]. There is a significant chance that the excess N applied will be lost to the environment because of the low nitrogen use efficiency (NUE) of crops and a high mobility of more reactive forms of N [58]. But frequent and excessive fertilizer use causes pollutants to build up in the soil that are hazardous to all environmental segments (e.g., water eutrophication, soil acidification and degradation, and air pollution) [59-62].

3.1: Air Pollution

The 21st century demands that air quality must be preserved for a sustainable and healthy way of life on Earth. However, actions such as the widespread manufacture and application of fertilizers add toxic pollutants such as particulates to the natural environment, disrupting the equilibrium of air quality constituents. Agricultural related activities like applying fertilizers, particularly nitrogenous ones, are linked to emissions of N_2O, CH_4, and CO_2. The major effect of inefficient nitrogen use is the release of different gases into the atmosphere, including NH_3, NO, and N_2O, which lowers the overall index of air quality [7]. Air gets polluted due to the emission of different gases by the applications of fertilizers, shown in figure 4(a) [63]. The health of people is directly impacted by air pollution. Air pollution-related diseases claimed the lives of five million people in 2017 [64].

3.1.1: Ammonia emission

Air contains primarily nitrogen in unreactive form (N_2). Ammonia, the form of nitrogen, is present in trace amounts in the atmosphere. This gas pollutes the environment if concentrations rise above a certain threshold. Low nitrogen use efficiency (NUE) also causes NH_3 to be released into the atmosphere, lowering the standard of air quality. High concentrations of NH_3 in the land and aquatic environment cause a number of environmental issues, including eutrophication and acidification, which lead to acid rain [7]. Ninety percent of the NH_3 emissions released into the atmosphere come from agriculture. Air quality is a major concern at the international level due to ammonia emissions.

3.1.2: Nitrous oxide emission

Worldwide, overall, about 50–60% of N_2O is released from soils. Nitrous oxide ranks as the third most significant greenhouse gas, after CO_2 and CH_3. Emissions of NO and N_2O lower air quality. Global warming is the result of the radial absorption of infrared radiation by N_2O. Moreover, N_2O is the main source in the stratosphere and hence has the greatest impact on ozone depletion. When solid fertilizer, specifically ammonium nitrate, is applied to fields, an abiotic mechanism also plays a role in the production of N_2O in addition to the biotic ones. The amount and method of application of nitrogen fertilizers affect N_2O emissions [7]. Nitrous oxide, which is released by fertilizer application, acts as a significant contributor to both greenhouse gas concentrations and ozone depletion on earth. The increased use of nitrogen fertilizers on a global scale has led to a rise in the atmospheric concentration of N_2O, which continues to be an effective greenhouse gas that is 298 times stronger than carbon dioxide [65]. Researcher conducted the first worldwide evaluation of nitrous oxide, which is the main greenhouse gas responsible for global warming [66]. Most of the N_2O pollution is caused by agricultural activities. Typically, between 20 and 70 percent of fertilizer is released into the environment as pollutants, greenhouse gases, and dissolved nutrients in most regions [67]. Fertilizer has detrimental effects on acid rain and global warming. An important contributing factor to ozone layer depletion is thought to be rising atmospheric N_2O. Agricultural practices globally contribute to nearly 15% of yearly greenhouse gas emissions.

3.1.3: Nitric oxide (NO) emission

NO is the form of nitrogen that is present in trace amounts. This gas contaminates the environment if its concentration rises in the atmosphere as a result, index of air quality reduces. NO contributes to the production of ozone in the troposphere region, a significant atmospheric pollutant that is harmful. Moreover, NO is a prominent precursor of HNO_3, the primary component of acid rain. Acidification and eutrophication are two of the numerous environmental issues due to excessive amounts of NO [7].

3.2: Soil pollution

Soil is made up of various elements like minerals, organic matter, gas, and water. Soil pollution can arise from multiple sources, including emissions from industries, waste containing heavy metals, gasoline, fertilizer application, sewage sludge, pesticides, irrigation of wastewater, residues from coal combustion, and so on. Heavy metal levels, especially those of cadmium, lead, and arsenic in soil, may rise as a result of such applications [68]. Nitrogenous fertilizers are applied in ammonium form, which is then oxidized to produce H^+, causing the pH of the soil to decrease, which in turn initiates the phase of soil acidification represented in figure 4 (b) [63]. When the soil becomes overly basic or acidic, microorganisms cannot thrive because enzymatic activities are influenced by fertilizers [7].

Consequently, applying fertilizer N may speed up the breakdown of organic matter in soil and negatively impact soil health [2]. The quality of groundwater may further deteriorate as a result of the expanding soil contamination, which must be prevented by applying organic manure, biofertilizer, and water under strict control [69-70].

3.3: Aquatic Ecosystem Pollution

An ecosystem is disturbed when chemical fertilizers are applied more often than plants require. When nitrogenous fertilizers are used excessively, the concentration of undesirable chemical species increase in ground and surface water, which lowers the quality of the water. Since nitrate is a stable form of nitrogen, but an excessive amount disturbs the delicate balance of aquatic ecosystems, it is an essential indicator for assessing the degree of pollution in environment [71-72]. Merely 30-50% of nitrogenous fertilizers are absorbed by plants, with the remaining 2-10% finding their way into surface and groundwater. A portion of the applied nitrogen also evaporated into the atmosphere. Excessive agricultural inputs of N and P have been found in waterbodies, leading to numerous negative consequences in water reservoirs. The amount of NO_3^- disposal in groundwater and the amount of N and P entering surface water rise in direct proportion to the over application of chemical fertilizers. Nitrogenous fertilizers cause the quality of the water to decline [7].

Just 50% of nitrogenous fertilizers that are applied to the soil are utilized by plants, and over half of the nitrogen fertilizer that is generated annually is lost [73]. Of this loss, 15–25% react with organic substances in soil, 2–20% evaporate, and the rest of 2–10% seep into the surface and groundwater [74]. Water outflows from agricultural areas are therefore responsible for 50–70% of nitrogen compound pollution in the environment [50-75]. Because nitrate is extremely soluble, it can be readily leached into aquatic ecosystems. Ammonia and N oxides are highly volatile, allowing them to be carried through the atmosphere [18-19].

3.3.1: Nutrient leaching and eutrophication

Unused nitrogen and certain other fertilizer nutrients find their way into surface and groundwater through various routes, such as leaching and surface runoff caused by irrigation techniques and rainfall. These nutrients become enriched and cause eutrophication when they get to neighboring ponds, lakes, and water bodies. Cyanobacteria and unwanted weed growth break down the organic material. Decomposition of organic matter results in the breakdown of dissolved oxygen (DO), which is found in water bodies. Additionally, ground and surface water are contaminated by NO_3^- from the soil through the leaching process. Aquatic species find it harder to survive when NO_2^-, which may seep from soil into surface water, undergoes oxidation by DO to NO_3^-. As a result, the amount of DO in waterbodies drops. Algal blooming is determined by nutrient ratios. The biodiversity of aquatic organisms may be lost as a result of excessive eutrophication, as illustrated in figure 5 [7] , which can cover all or a portion of the surface in extreme cases with algae. This prevents sunlight from penetrating the bottom surface of water bodies. Lack of oxygen causes native aquatic species to vanish. Furthermore, the release of different smelly substances by cyanobacteria causes natural ecosystems to become unpleasant [76-77]. Due to erosion, the components of mineral fertilizers flow from the soil into aquatic environments. It accelerates the eutrophication and contamination of sea and surface waters [73-75-78]. The biological state of the water body as well as the local climate and temperature all affect eutrophication.

4. Microbiological impact of fertilizers on microbial diversity

One of the main elements that determines the biological nature of soil is the diversity of microorganisms present in it. Of all the microorganisms found in soil, the population of fungi and bacteria is very important. Nutrients and substances that encourage plant growth are provided by certain bacteria. It has been widely demonstrated that by providing nutrients, certain microbial communities can grow more quickly when both chemical and organic fertilizers are applied [79], increasing the overall number of microorganisms [80-82]. Actually, it has been found that higher microbial biomass leads to improved plant growth [9]. It is observed that organic fertilizers improve the physical and chemical characteristics of soil more than inorganic fertilizers by raising microbial activity. In addition, the capacity of soil to store nutrients and the rate at which waste is broken down by soil microorganisms both influence the biological condition of soil. Microorganisms are involved in the cycling of nutrients, chemical conversion, and breakdown of organic matter.

Excessive chemical fertilizers can alter the overall microbial biomass or the population of a specific type of microorganism in a field [83]. Due to the pH dependence of microorganisms, fertilizer application can cause the soil to become excessively basic or acidic, which will prevent the microorganisms from surviving [7]. Mineral fertilizers decrease microbial diversity, particularly the microbial taxa that are beneficial to plants [84]. The two main variables affecting the number of microbial communities are total available nitrogen and phosphorous in soil [85]. When mineral fertilizers are applied over an extended period of time, different microbial groups react in different ways. The population of soil microorganisms, structure, number, and activity are impacted by mineral fertilizers. The quantity, and method of fertilizer applied can all affect the soil biota in different ways and for different lengths of time.

4.1: Influence of fertilizers on enzymatic activity

Soil microorganisms have dehydrogenase enzymes for the biological oxidation of organic substances, which are only found in live cells of microbes. Dehydrogenase activity (DHA) is a sign of soil microbial activity [86-87] which is inhibited by the use of high concentrations of NPK fertilizers [9]. Furthermore, along with the biomass of soil microbes and bacterial diversity, long-term phosphorous-deficient fertilizers may drastically decrease dehydrogenase activity (DHA) [88]. While balanced NPK fertilization can raise DHA levels, organic fertilizers consistently result in a greater increase in DHA. The soil microbial community may undergo structural and functional changes as a result of mineral fertilizers, which alter the amount of available N and P and, consequently, vary soil fertility. Moreover, the combination of N, P, and K applications increases the biomass of soil microbes and diversifies bacterial communities [9]. The addition of organic matter promotes microbial activity, which is correlated with soil quality and quantified by dehydrogenase activity. Certain enzymes found in soil, like β-glycosidase and phosphatase, break down organic acids to produce acetic acid. Consequently, enzymatic activity increases with increasing nitrogen addition to the soil. As a result, the production of acetic acid rises, which in turn causes the production of methane and starts the phase of soil acidification [89].

4.2: Impact of N fertilizers on the Nitrogen Cycle

Nitrogenous fertilizers have significant impact on nitrogen cycle. The nitrogen cycle depends on the redox conversion of nitrogen compounds, and a wide variety of microorganisms, particularly bacteria and archaea. Natural cycles of nitrogen, such as nitrification, ammonification, assimilation, and denitrification, keep the constant amount of nitrogen in the environment. The atmosphere contains nitrogen in an inert state. Nitrogen is fixed by certain bacteria through a process known as ammonification, which turns nitrogen into ammonia. Plants can take nitrogen in different forms, like ammonium (NH_4^+) and nitrate (NO_3^-) [7].

Nitrogen cycle in soils is greatly impacted by extended chemical fertilization [90-93]. Prolonged use of chemical fertilizer has a substantial influence on soil microbial communities [94-95]. The biological functions of soil, such as enzymatic and aeration processes, can also be impacted by applying nitrogenous fertilizers. Greater ionic strength and ammonia release from overuse of urea and ammonium fertilizers inhibit soil microorganisms. Fertilizers containing nitrogen are frequently applied in the NH_4^+ form, which releases hydrogen ions upon oxidation, lowering the pH level of the soil and causing the loss of microbial diversity. Furthermore, the overuse of nitrogenous fertilizers resulted in a decrease in symbiotic organism activity, a decline in microbial biomass and the destruction of the bacterial community [7]. Application of fertilizers, especially N, may cause air contamination, soil acidification, which would inhibit microbial activity and growth and also become the reason for eutrophication due to leaching, as illustrated in figure 6 [96]. However, high rates of urea and ammonium fertilizers may kill soil microorganisms because of ammonia toxicity, pH, and greater ionic strength. Merely combining chemical as well as organic fertilization could promote microbial groups associated with the nitrogen cycle [9].

4.2.1: Effects on Ammonifying and Nitrifying Bacteria

The quantity and efficiency of ammonium oxidizers, along with those of other nitrifying organisms, are generally more positively impacted by N fertilizers. The combination of chemical and organic fertilization is the only way to enhance the significant ecological role of soil nitrification. When soil was treated with inorganic fertilizers, the number of active N-fixing cyanobacteria increased. Organic fertilizers enhance the growth of certain bacterial groups, including bacterioidetes, actinobacteria, gamma, and alpha proteobacteria [97]. Legumes possess the benefit of forming associations with particular soil rhizobial bacteria. These bacteria can utilize root nodules to store atmospheric nitrogen as ammonia, which can subsequently be integrated into organic elements like proteins and nucleic acids [98].

Ammonia-oxidizing bacteria (AOB) and ammonia-oxidizing archaea (AOA) are adversely affected by chemical fertilizers [85]. Microbial biomass in the soil and community composition can be significantly impacted in the short term by alterations in soil environment brought about by the use of urea and ammonium fertilizers. Most soil bacteria, Azotobacter being the most common, respond favorably to inorganic as well as organic fertilizers. The use of urea and ammonium is expected to be advantageous for other nitrifying species [99]. But greater ammonium concentrations caused the rate of nitrification to drop to nearly half of its maximum [100]. For instance, N fertilizers in calcareous soils raise the nitrification rate but decrease the efficiency of N utilization and modify the diversity of ammonia-oxidizing bacteria (AOB), elevating the overall number of Nitrosomonas (oxidize ammonia to nitrite) [91]. Mineral fertilization greatly enhanced the amount and variety of ammonia oxidizing bacteria, but had little effect on the community of ammonia oxidizing archaea [101].

4.3: Impact of fertilizers on the Phosphorous Cycle

Unlike other biogeochemical cycles, the phosphorus cycle does not produce any stable gaseous species. Phosphate and sedimentary rocks are the biggest sources of P in soil and the marine environment. Phosphorus-solubilizing microorganisms (PSMs), like bacteria and fungi, are essential to the P cycle because they mineralize organic P, dissolve inorganic P minerals, and store a significant quantity of P in biomass. These microorganisms not only provide soluble P but also help in plant growth. Soil P can be dissolved into soluble form by PSMs through the release of phosphatase enzymes and organic acids, which lower soil pH [102]. Synthetic fertilizers have an impact on soil phosphorus levels. But overuse of P fertilizers causes increasing P losses and decreasing microbial activity. A process known as eutrophication can occur when there is an excess of phosphorus in water bodies due to leaching or runoff, which promotes the growth of algae and lowers the dissolved oxygen level. Elevated phosphorus levels can also cause toxic algal blooms that can be dangerous for aquatic organisms in figure 7 [103].

The composition, variety, and relative abundance of a particular soil microbe community are all altered by chemicals fertilizers [104-105]. Distinct bacterial and microfungal groups can differ in their capacity to utilize various nutrient forms present in soil [84-88-106]. Long-term use of chemical fertilizers had a powerful impact on the structure of the microbial community [107].

5. Chemical implications of fertilizer consumption

Fertilizer industry produces chemical fertilizers, primarily made of nitrogen, phosphate, and potash [108].

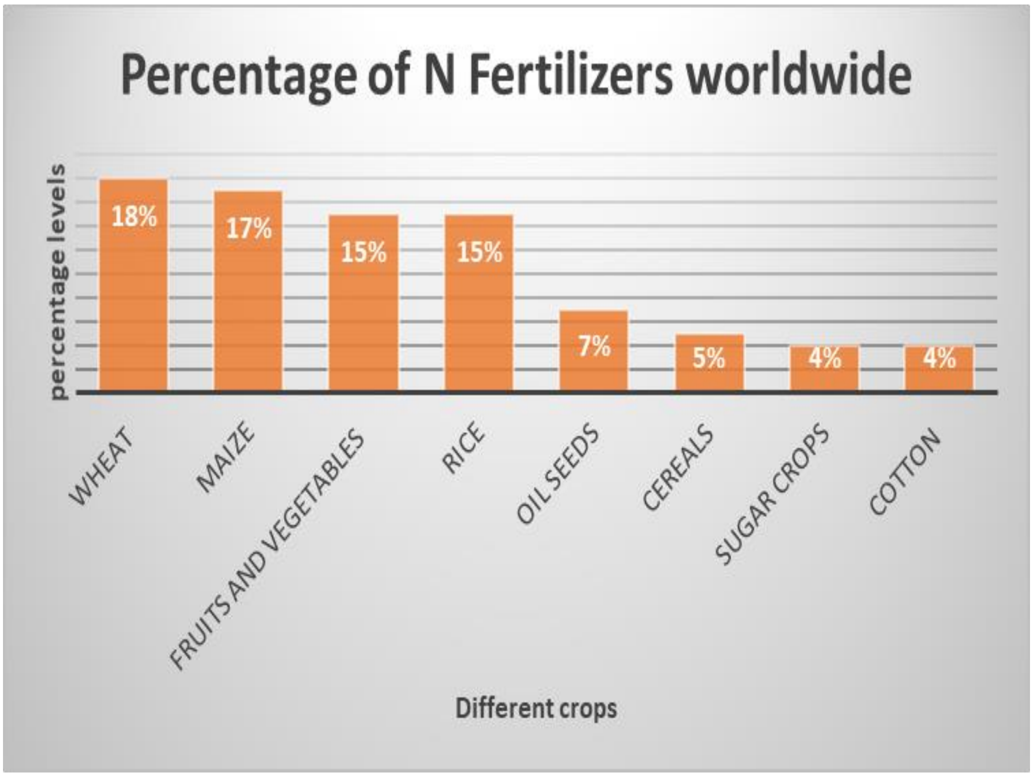

Figure 1: Graph representing worldwide distribution of Nitrogen (N)

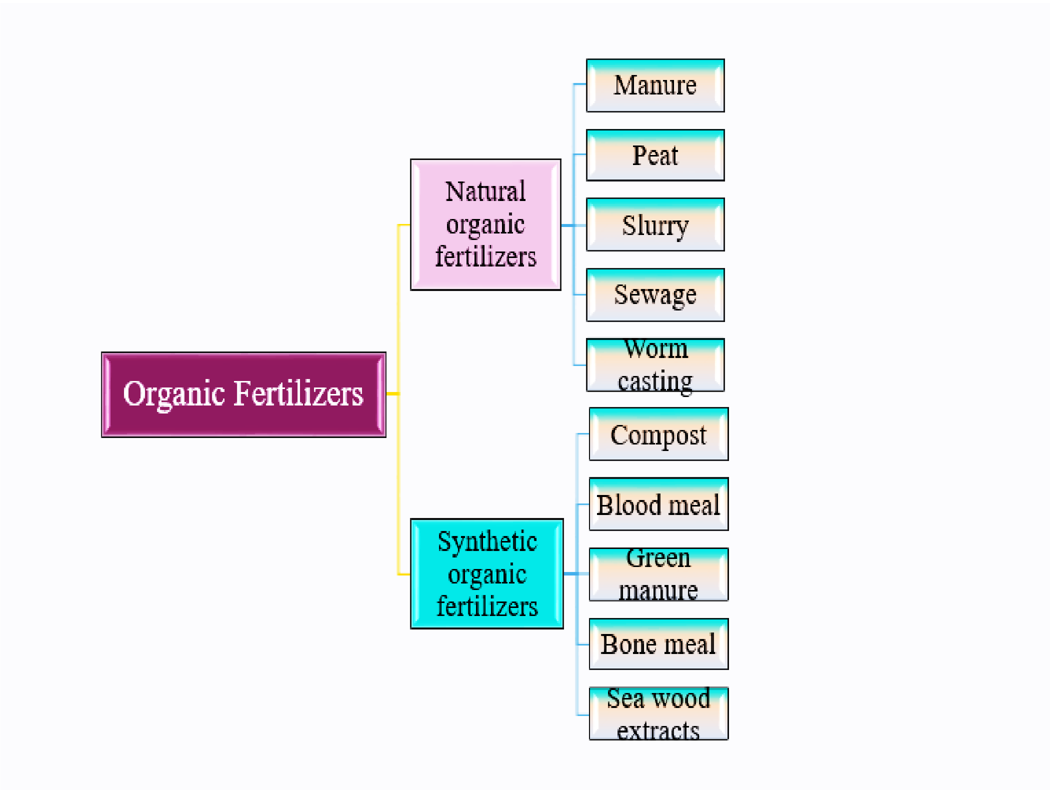

Figure 2. List of different sources of organic fertilizers

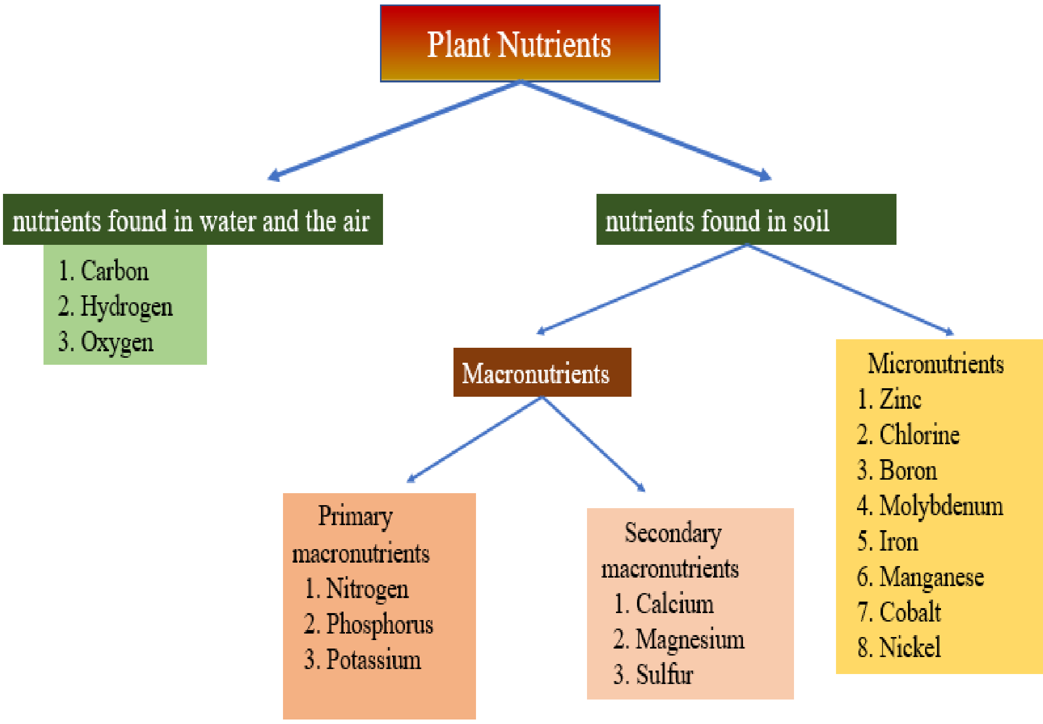

Figure 3. Classification of various important plant nutrients

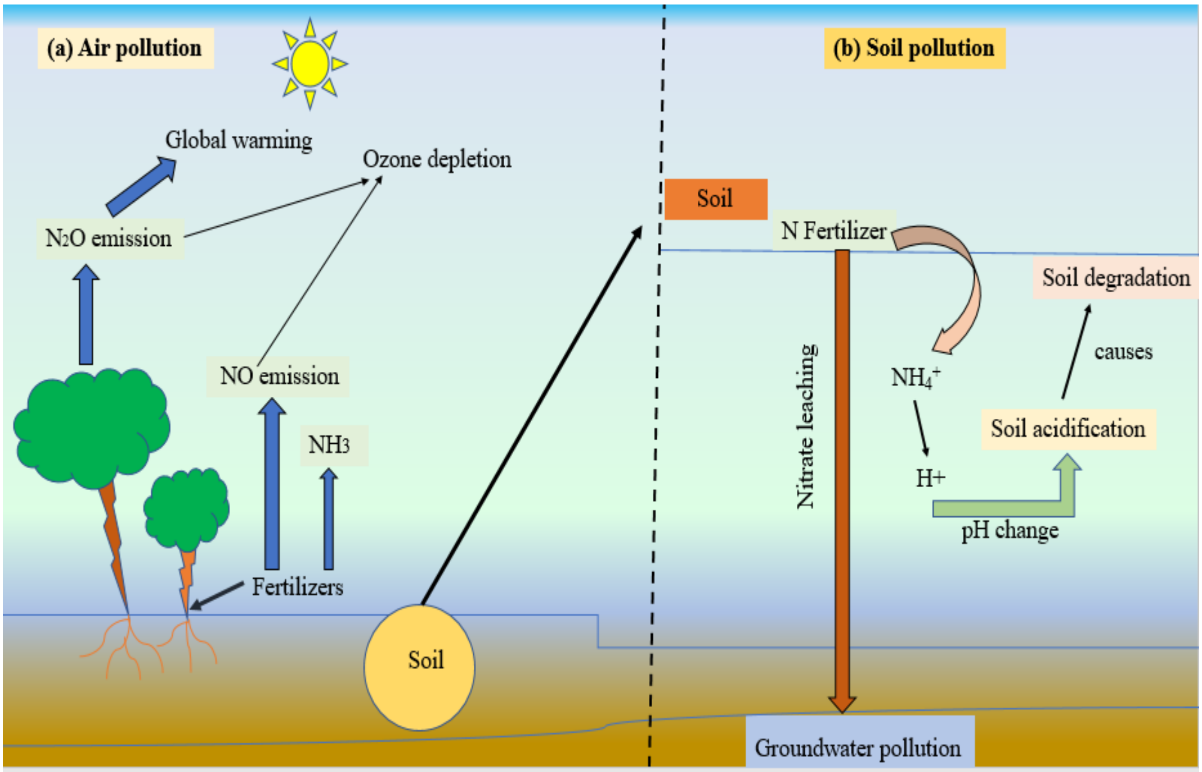

Figure 4. (a, b) Demonstrating the pollution of air and soil, respectively

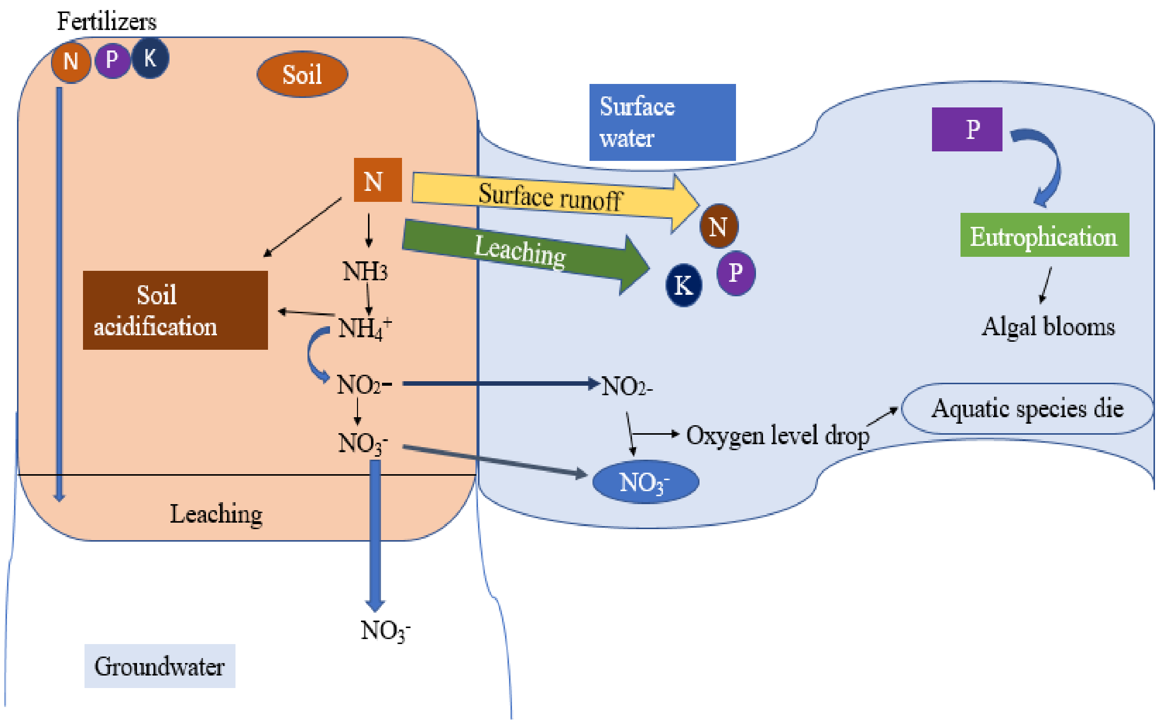

Figure 5. Water contamination resulting from overuse of fertilizers

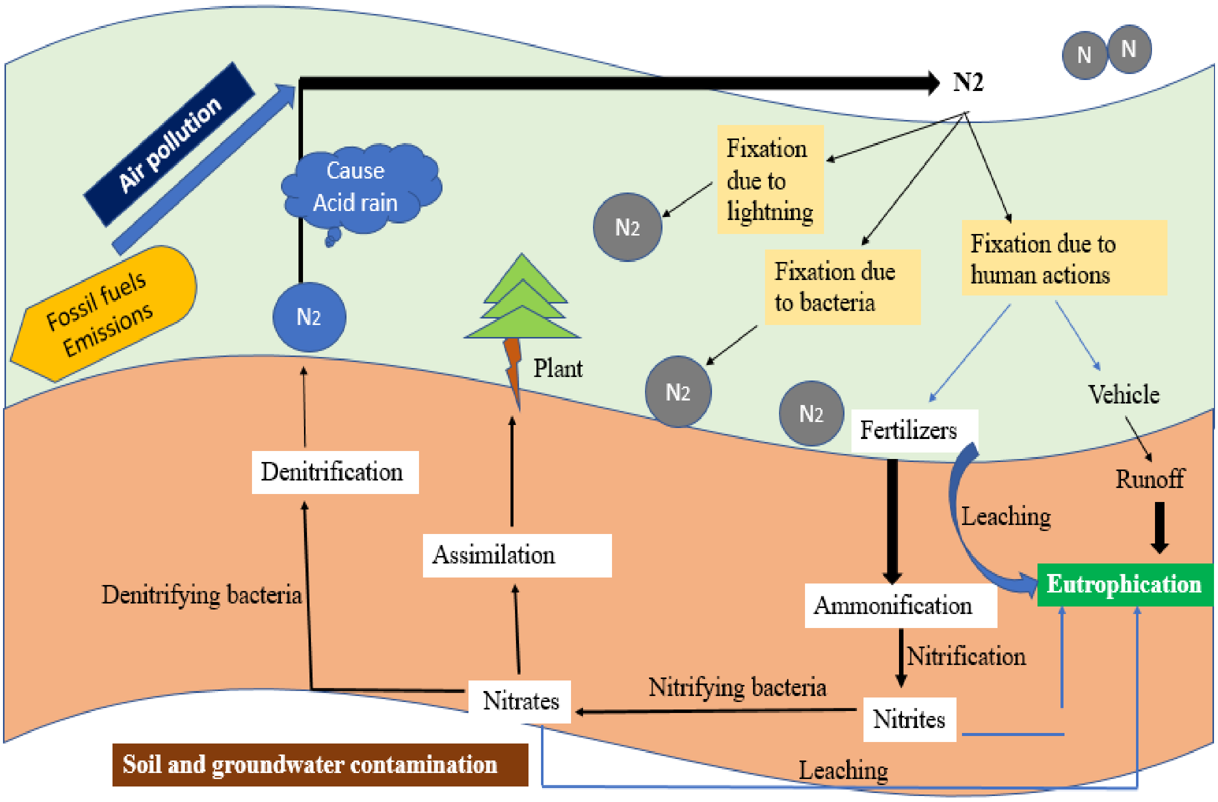

Figure 6. Nitrogen cycle demonstrating fertilizer effect

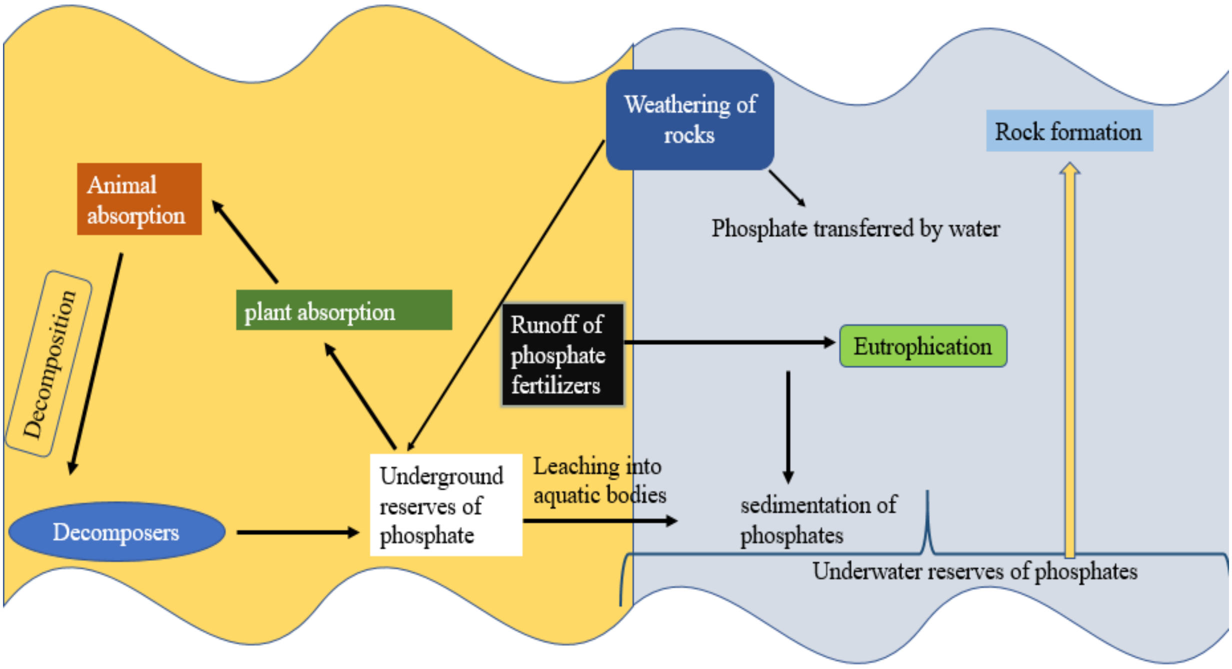

Figure 7. Overview of P cycle

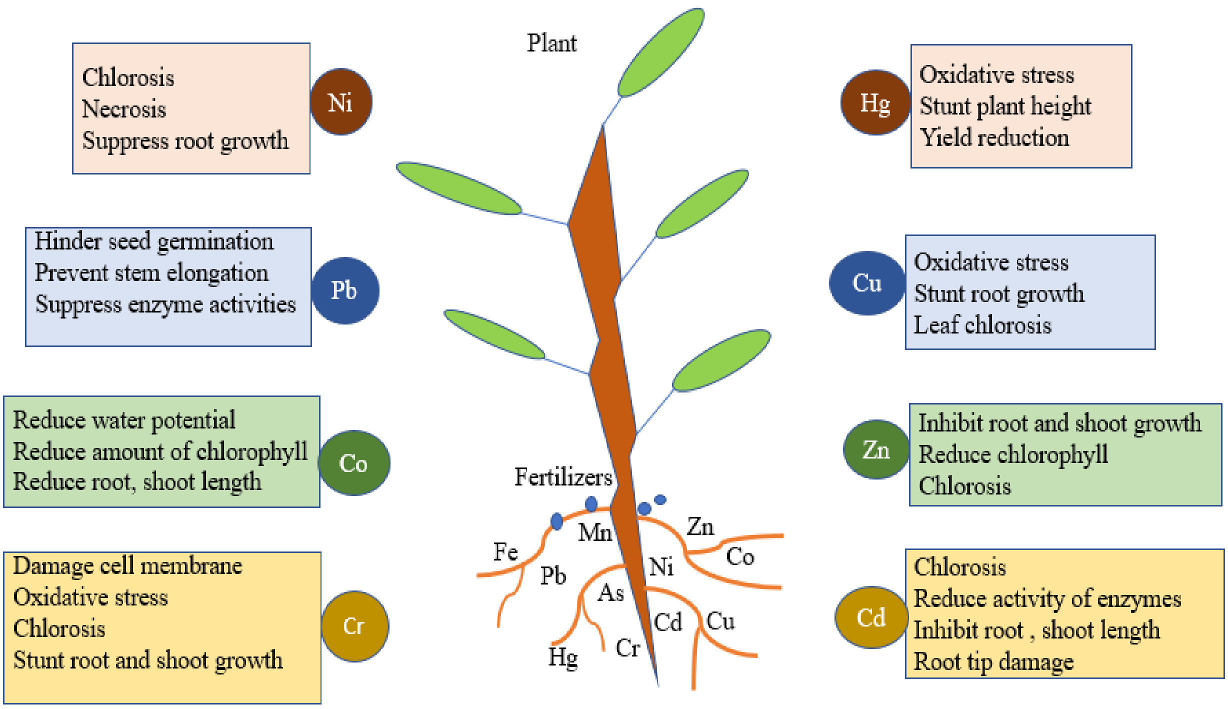

Figure 8. The harmful effects of various heavy metals on different plant parts

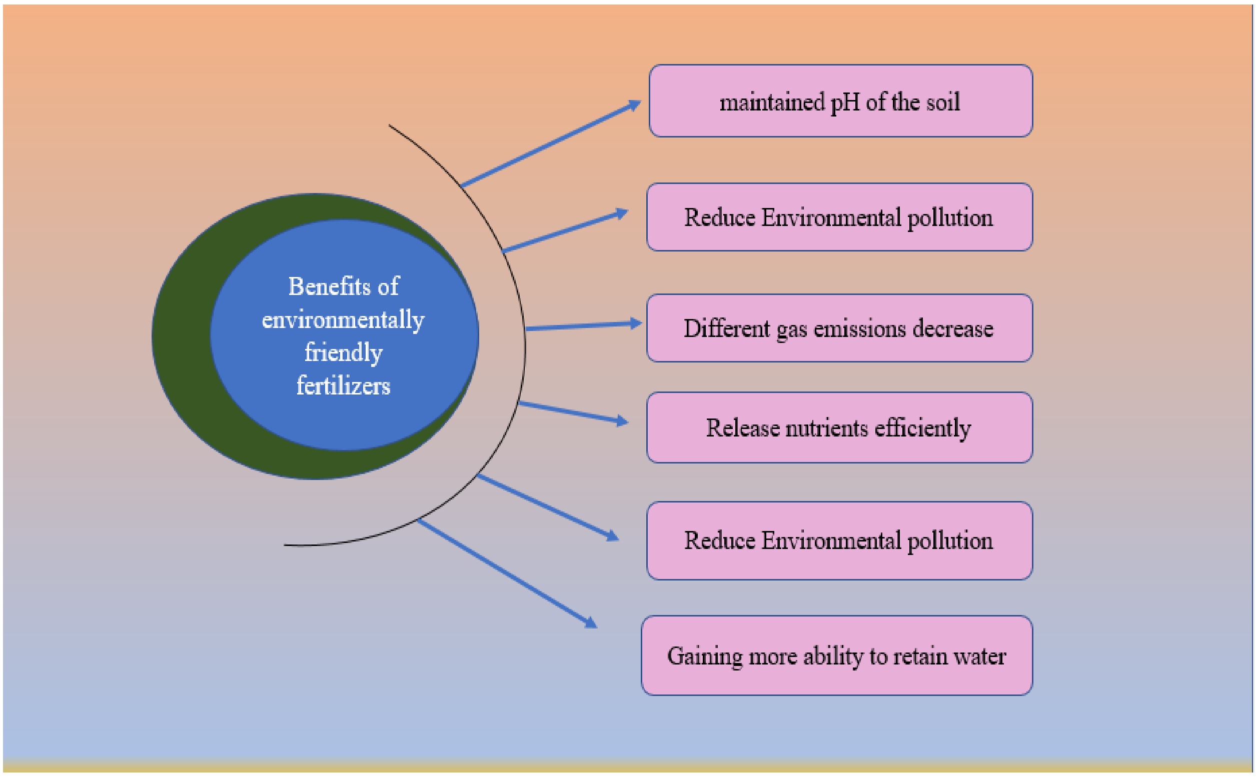

Figure 9. A brief summary of the positive consequences of EFFs

Table 1. Different types of inorganic fertilizers

Inorganic fertilizers	Examples	Different levels
Nitrogen based fertilizers	1.Zwaveluur Ammonium (ZA) 2.Urea 3.Chile saltpetre 4. NH_4NO_3	21% N 45% N 15% N 35% N
Phosphorous based fertilizers	1.Superphosphate multiple 2.Triple superphosphate	30% P_2O_5 45% P_2O_5
Potash based fertilizers	1. KCl 2. Potassium Sulphate	50% K_2O 50% K_2O

The use of chemical fertilizers is generally regarded as a key solution for the problem of depletion of nutrients and maintaining food production [109]. Improving the functions of ecosystems in any food production process while preventing adverse effects on the environment requires the most efficient utilization of synthetic fertilizers [110]. But many issues, including salinity in the soil, heavy metal and nitrate accumulation, eutrophication of water bodies, and pollution in the atmosphere, are brought on by the excessive use of chemical fertilizers. Mineral fertilizers reduce the permeability and availability of nutrients in soil [111]. Furthermore, the quantity and quality of entire population of soil microorganisms are both significantly impacted by mineral fertilizers. They increase gaseous losses of nitrogen and degrade the physical, chemical, and biological qualities of the soil and also produce toxic heavy metals in soil.

8.1: Heavy metal contamination

Environment is getting more polluted due to massive economic development and quick expansion in many sectors, like agriculture and industry [112]. Naturally, metals with a large atomic weight are classified as heavy metals [113]. They are necessary for many plant organs, but when concentrations of these elements rise above recommended limits, they become toxic. Fertilizers cause the production of heavy metals in soil, which include both organic and inorganic components. When phosphorus containing fertilizers are added to soil, they contribute to the accumulation of heavy metals [114]. Environment and health issues caused by cadmium (Cd), lead (Pb), copper (Cu), and zinc (Zn) are alarming [113-115]. When phosphate fertilizers are used continuously, heavy metals accumulate, which harm plants and pollute the food supply [116]. On average, phosphate fertilizers contain small amounts of heavy metals, such as arsenic, copper, chromium, zinc, cadmium, and palladium [60-61]. Fertilizer application for a long period of time has raised the possibility of Cu, Zn, and Cd buildup in agricultural soil [117]. Due to prolonged excessive fertilizer use, soil fertility is reduced due to heavy metals , which affect plant growth and productivity [118]. These metals damage plants and can also be harmful to human health because they are absorbed through the food chain [119]. When soil is contaminated with heavy metals, it is very difficult to restore soil environment. As a result of heavy metals entering the soil, the risk of environmental pollution has been rising quickly recently, particularly in the agricultural sector [37]. The negative effects of different heavy metals on different plant parts are shown in figure 8 [120].

8.2: Soil health declines due to chemical effects

Soil is home to a variety of chemical reactions, some of which can be disturbed by overuse of fertilizers due to pH imbalance. Adding fertilizers to the soil not only improves crop yields but also modifies its physiochemical and biological characteristics. However, the ongoing application of synthetic fertilizers causes a reduction in soil organic matter and the deterioration of agricultural soil quality. The frequent application of chemical fertilizers causes environmental risks by hardening the soil, decreasing soil fertility, polluting the environmental components, and reducing vital soil and mineral nutrients. Chemical fertilizers can alter the pH of soil, kill beneficial organisms, stunt plant growth, and even contribute to greenhouse gas emissions [36].

6. Solution and control measures

Using advanced fertilizers is a practical way to reduce the negative environmental effects of conventional fertilizers and increase their efficiency [121]. The following section discusses various strategies that are crucial to the agricultural industry because they boost product yield while reducing the negative effects of chemicals on the environment and soil microorganisms.

6.1: Use of environmentally friendly fertilizers (EFFs)

In order to preserve soil fertility, boost yields, and enhance harvest quality, fertilizer is essential. Unfortunately, a large amount of fertilizer is wasted, which raises the cost of farming, wastes energy, and pollutes the environment, all of which pose threats to the sustainability of the modern agricultural sector. EFFs are typically designed by coating the nutrients with eco-friendly materials that break down in the soil to produce CO_2, CH_4, H_2O, inorganic compounds, or microbial biomass. This is the most widely used and accessible formulation. They provide an efficient means of enhancing nutrient efficiency, minimizing fertilizer leaching and volatilization losses, and lowering environmental risks. Even different N emissions, like NO_x and N_2 can be diminished with the help of these fertilizers. By regulating the release of nutrients into the soil, they lessen pollution from nutrient losses into the environment with a lot of other valuable benefits, as summarized in figure 9 [122-123].

6.1.1: Controlled release nanofertilizers (CRNFs)

CRNFs are considered environmentally friendly fertilizers because they release nutrients in a controlled manner based on plant requirements by mitigating the chance of nutrient loss. Nanotechnology has been extremely important in this regard in recent decades [124]. It is one of the most exciting developments, not only for reducing overuse of conventional fertilizers but also for improving significant environmental challenges and microbial activity [125].

6.1.2: Promoting Organic Agriculture

Organic farming reduces all forms of environmental contamination, making it a sustainable and safe way to increase the supply of food [126]. Farmers may lessen the hazards to the global environment by employing organic farming practices [127]. Prefer organic fertilizers over chemical fertilizers because they enhance the level of organic matter, and micronutrients in soil. Organic farming methods help enhance the biodiversity of the soil and its quality [128].

7. Conclusions

Sustainable agriculture is essential to reducing hunger and boosting food security worldwide. Thus, fertilizers are necessary to increase crop yield and meet worldwide food demand. However, excessive application of conventional fertilizers affected microbial diversity in addition to causing serious environmental pollution, including poor air quality, contaminated soil with heavy metals, nutrient leaching, and disruption of the nutrient cycle. To reduce these effects, it is advised to create an effective approach in order to improve both environmental quality and crop productivity. Organic farming reduces a lot of issues relating to the environment. Precision farming practices has been made possible specifically by using environmentally friendly fertilizers (EFFs) as they offer an effective way of increasing nutrient-use efficiency, minimizing the leaching of essential nutrients, lowering toxicity and environmental hazards. By using the rapidly developing nanoscience field, nanofertilizers with controlled release of nutrients are also included in EFFs. They propose a clean, safe, and healthy environment by increasing beneficial microbial activity and lowering hazardous environmental effects .

References:

[1] H. Chhipa. (2017). Nanofertilizers and nanopesticides for agriculture. Environmental chemistry letters. 15: 15-22.

[2] B.-. Singh. (2018). Are nitrogen fertilizers deleterious to soil health? Agronomy. 8(4): 48.

[3] D. Krein, M. Rosseto, F. Cemin, L. Massuda, A. Dettmer. (2023). Recent trends and technologies for reduced environmental impacts of fertilizers: a review. International Journal of Environmental Science and Technology. 1-16.

[4] K. Chojnacka, K. Gorazda, A. Witek-Krowiak, K. Moustakas. (2019). Recovery of fertilizer nutrients from materials-Contradictions, mistakes and future trends. Renewable and Sustainable Energy Reviews. 110: 485-498.

[5] S. Nadarajan, S. Sukumaran, Chemistry and toxicology behind chemical fertilizers. In *Controlled Release fertilizers for sustainable agriculture*, Elsevier: 2021; pp 195-229.

[6] D. Geisseler, K.M. Scow. (2014). Long-term effects of mineral fertilizers on soil microorganisms–A review. Soil Biology and Biochemistry. 75: 54-63.

[7] J. Tyagi, S. Ahmad, M. Malik. (2022). Nitrogenous fertilizers: Impact on environment sustainability, mitigation strategies, and challenges. International Journal of Environmental Science and Technology. 19(11): 11649-11672.

[8] W.-f. Zhang, Z.-x. Dou, P. He, X.-T. Ju, D. Powlson, D. Chadwick, D. Norse, Y.-L. Lu, Y. Zhang, L. Wu. (2013). New technologies reduce greenhouse gas emissions from nitrogenous fertilizer in China. Proceedings of the National Academy of Sciences. 110(21): 8375-8380.

[9] L.C. Dincă, P. Grenni, C. Onet, A. Onet. (2022). Fertilization and soil microbial community: a review. Applied Sciences. 12(3): 1198.

[10] S. Karimi, S. Soltani, K. Jasemi. (2023). Positive and Negative Impact of Nitrogen Fertilizer on Soil Properties and Nutrient Dynamic. Asian Journal of Research in Agriculture and Forestry. 9(3): 233-240.

[11] M. Elkholy, S.E. Mahrous, S. El-Tohamy. (2010). Integrated effect of mineral, compost and biofertilizers on soil fertility and tested crops productivity. Research Journal of Agriculture and Biological Sciences. 5: 453-465.

[12] B. Vanlauwe, A. Bationo, J. Chianu, K.E. Giller, R. Merckx, U. Mokwunye, O. Ohiokpehai, P. Pypers, R. Tabo, K.D. Shepherd. (2010). Integrated soil fertility management: operational definition and consequences for implementation and dissemination. Outlook on agriculture. 39(1): 17-24.

[13] T.B. Roba. (2018). Review on: The effect of mixing organic and inorganic fertilizer on productivity and soil fertility. Open Access Library Journal. 5(06): 1.

[14] N. Ling, Y. Sun, J. Ma, J. Guo, P. Zhu, C. Peng, G. Yu, W. Ran, S. Guo, Q. Shen. (2014). Response of the bacterial diversity and soil enzyme activity in particle-size fractions of Mollisol after different fertilization in a long-term experiment. Biology and fertility of soils. 50: 901-911.

[15] J. Shrestha, K.K. Shah, K.P. Timsina. (2020). Effects of different fertilizers on growth and productivity of rice (Oryza sativa L.): A review. International Journal of Global Science Research. 7(1): 1291-1301.

[16] R. Chai, X. Ye, C. Ma, Q. Wang, R. Tu, L. Zhang, H. Gao. (2019). Greenhouse gas emissions from synthetic nitrogen manufacture and fertilization for main upland crops in China. Carbon balance and management. 14(1): 1-10.

[17] E. Craswell. (2021). Fertilizers and nitrate pollution of surface and ground water: an increasingly pervasive global problem. SN Applied Sciences. 3(4): 518.

[18] G. Billen, J. Garnier, L. Lassaletta. (2013). The nitrogen cascade from agricultural soils to the sea: modelling nitrogen transfers at regional watershed and global scales. Philosophical Transactions of the Royal Society B: Biological Sciences. 368(1621): 20130123.

[19] J. Martínez-Dalmau, J. Berbel, R. Ordóñez-Fernández. (2021). Nitrogen fertilization. A review of the risks associated with the

inefficiency of its use and policy responses. Sustainability. 13(10): 5625.
[20] S. GSBI. (2020). State of knowledge of soil biodiversity–Status, challenges and potentialities. Summary for policy makers.
[21] F.B. Lewu, T. Volova, S. Thomas, R. Rakhimol. (2020). Controlled release fertilizers for sustainable agriculture. Academic Press: pp.
[22] J. Mercado-Blanco, I. Abrantes, A. Barra Caracciolo, A. Bevivino, A. Ciancio, P. Grenni, K. Hrynkiewicz, L. Kredics, D.N. Proença. (2018). Belowground microbiota and the health of tree crops. Frontiers in Microbiology. 9: 1006.
[23] R. Mendes, P. Garbeva, J.M. Raaijmakers. (2013). The rhizosphere microbiome: significance of plant beneficial, plant pathogenic, and human pathogenic microorganisms. FEMS microbiology reviews. 37(5): 634-663.
[24] M. Ahemad, M. Kibret. (2014). Mechanisms and applications of plant growth promoting rhizobacteria: current perspective. Journal of King saud University-science. 26(1): 1-20.
[25] E.H. Verbon, L.M. Liberman. (2016). Beneficial microbes affect endogenous mechanisms controlling root development. Trends in plant science. 21(3): 218-229.
[26] R. Jacoby, M. Peukert, A. Succurro, A. Koprivova, S. Kopriva. (2017). The role of soil microorganisms in plant mineral nutrition—current knowledge and future directions. Frontiers in plant science. 8: 1617.
[27] M. Islam, M. Hossain, A. Siddique, M. Rahman, M. Malika. (2014). Contribution of green manure incorporation in combination with nitrogen fertilizer in rice production. SAARC Journal of Agriculture. 12(2): 134-142.
[28] M. Skorupka, A. Nosalewicz. (2021). Ammonia volatilization from fertilizer urea—a new challenge for agriculture and industry in view of growing global demand for food and energy crops. Agriculture. 11(9): 822.
[29] A. Lateef, R. Nazir, N. Jamil, S. Alam, R. Shah, M.N. Khan, M. Saleem. (2019). Synthesis and characterization of environmental friendly corncob biochar based nano-composite–A potential slow release nano-fertilizer for sustainable agriculture. Environmental Nanotechnology, Monitoring & Management. 11: 100212.
[30] S. Gupta, M. Kumar, J. Kumar, V. Ahmad, R. Pandey, N. Chauhan. (2017). Systemic analysis of soil microbiome deciphers anthropogenic influence on soil ecology and ecosystem functioning. International Journal of Environmental Science and Technology. 14: 2229-2238.
[31] J. Huang, H. Richard, S. Zheng. (2014). Effects of nitrogen fertilization on soil labile carbon fractions of freshwater marsh soil in Northeast China. International Journal of Environmental Science and Technology. 11: 2009-2014.
[32] J. Pushpamalar, S. Langford, M. Ahmad, Y. Lim, K. Hashim. (2018). Eco-friendly smart hydrogels for soil conditioning and sustain release fertilizer. International Journal of Environmental Science and Technology. 15: 2059-2074.
[33] Y. Wu. (2011). Chemical fertilizer use efficiency and its determinants in China's farming sector: Implications for environmental protection. China Agricultural Economic Review. 3(2): 117-130.
[34] V. Nsengimana, J. de Dieu Nsenganeza, T. Hagenimana, W. Dekoninck. (2023). Impact of chemical fertilizers on diversity and abundance of soil-litter arthropod communities in coffee and banana plantations in southern Rwanda. Current Research in Environmental Sustainability. 5: 100215.
[35] G. Dar, A. Kamili, M. Chishti, S. Dar, T. Tantry, F. Ahmad. (2016). Characterization of Aeromonas sobria isolated from fish Rohu (Labeo rohita) collected from polluted pond. J Bacteriol Parasitol. 7(3): 1-5.
[36] H.N. Pahalvi, L. Rafiya, S. Rashid, B. Nisar, A.N. Kamili. (2021). Chemical fertilizers and their impact on soil health. Microbiota and Biofertilizers, Vol 2: Ecofriendly Tools for Reclamation of Degraded Soil Environs. 1-20.
[37] G. Tóth, T. Hermann, M.R. Da Silva, L. Montanarella. (2016). Heavy metals in agricultural soils of the European Union with implications for food safety. Environment international. 88: 299-309.
[38] A. Alengebawy, S.T. Abdelkhalek, S.R. Qureshi, M.-Q. Wang. (2021). Heavy metals and pesticides toxicity in agricultural soil and plants: Ecological risks and human health implications. Toxics. 9(3): 42.
[39] A.O. Adesemoye, J.W. Kloepper. (2009). Plant–microbes interactions in enhanced fertilizer-use efficiency. Applied microbiology and biotechnology. 85: 1-12.
[40] I. Rautela, P. Dheer, P. Thapliyal, D. Shah, M. Joshi, S. Upadhyay, P. Gururani, V.B. Sinha, N. Gaurav, M.D. Sharma. (2021). Current scenario and future perspectives of nanotechnology in sustainable agriculture and food production. Plant Cell Biotechnol. Mol. Biol. 22: 99-121.

[41] G. Hazra. (2016). Different types of eco-friendly fertilizers: An overview. Sustainability in Environment. 1(1): 54.
[42] S. Iqbal, H.I. Tak, A. Inam, A. Inam, S. Sahay, S. Chalkoo. (2015). Comparative effect of wastewater and groundwater irrigation along with nitrogenous fertilizer on growth, photosynthesis and productivity of chilli (Capsicum annuum L.). Journal of Plant Nutrition. 38(7): 1006-1021.
[43] C.O. Dimkpa, J. Fugice, U. Singh, T.D. Lewis. (2020). Development of fertilizers for enhanced nitrogen use efficiency–Trends and perspectives. Science of the Total Environment. 731: 139113.
[44] M. Rajan, S. Shahena, V. Chandran, L. Mathew, Controlled release of fertilizers—concept, reality, and mechanism. In *Controlled release fertilizers for sustainable agriculture*, Elsevier: 2021; pp 41-56.
[45] A. Sharma, R. Chetani. (2017). A review on the effect of organic and chemical fertilizers on plants. Int. J. Res. Appl. Sci. Eng. Technol. 5: 677-680.
[46] J.C. Cole, M.W. Smith, C.J. Penn, B.S. Cheary, K.J. Conaghan. (2016). Nitrogen, phosphorus, calcium, and magnesium applied individually or as a slow release or controlled release fertilizer increase growth and yield and affect macronutrient and micronutrient concentration and content of field-grown tomato plants. Scientia horticulturae. 211: 420-430.
[47] S. Shahena, M. Rajan, V. Chandran, L. Mathew, Conventional methods of fertilizer release. In *Controlled release fertilizers for sustainable agriculture*, Elsevier: 2021; pp 1-24.
[48] M.M. Rashid, M. Jahan, K.S. Islam. (2016). Impact of nitrogen, phosphorus and potassium on brown planthopper and tolerance of its host rice plants. Rice Science. 23(3): 119-131.
[49] K. Tadesse, D. Habte, W. Admasu, A. Admasu, B. Abdulkadir, A. Tadesse, A. Mekonnen, A. Debebe. (2021). Effects of preceding crops and nitrogen fertilizer on the productivity and quality of malting barley in tropical environment. Heliyon. 7(5).
[50] T.G. Abebe, M.R. Tamtam, A.A. Abebe, K.A. Abtemariam, T.G. Shigut, Y.A. Dejen, E.G. Haile. (2022). Growing use and impacts of chemical fertilizers and assessing alternative organic fertilizer sources in Ethiopia. Applied and Environmental Soil Science. 2022: 1-14.
[51] K. Chojnacka, K. Moustakas, A. Witek-Krowiak. (2020). Bio-based fertilizers: A practical approach towards circular economy. Bioresource Technology. 295: 122223.
[52] H. Wu, G.K. MacDonald, J.N. Galloway, L. Zhang, L. Gao, L. Yang, J. Yang, X. Li, H. Li, T. Yang. (2021). The influence of crop and chemical fertilizer combinations on greenhouse gas emissions: A partial life-cycle assessment of fertilizer production and use in China. Resources, Conservation and Recycling. 168: 105303.
[53] I. Álvarez-Manzaneda, N. Laza, F.B. Navarro, E. Suárez-Rey, M.L. Segura, I. de Vicente. (2021). Assessing the viability of recovered phosphorus from eutrophicated aquatic ecosystems as a liquid fertilizer. Journal of Environmental Management. 285: 112156.
[54] S.Z. Sattari, A.F. Bouwman, K.E. Giller, M.K. van Ittersum. (2012). Residual soil phosphorus as the missing piece in the global phosphorus crisis puzzle. Proceedings of the National Academy of Sciences. 109(16): 6348-6353.
[55] J. Lienert, T.A. Larsen. (2010). High acceptance of urine source separation in seven European countries: a review. Environmental science & technology. 44(2): 556-566.
[56] M. Bamsey, T. Graham, C. Thompson, A. Berinstain, A. Scott, M. Dixon. (2012). Ion-specific nutrient management in closed systems: the necessity for ion-selective sensors in terrestrial and space-based agriculture and water management systems. Sensors. 12(10): 13349-13392.
[57] P. Barłóg, W. Grzebisz. (2004). Effect of timing and nitrogen fertilizer application on winter oilseed rape (Brassica napus L.). II. Nitrogen uptake dynamics and fertilizer efficiency. Journal of Agronomy and Crop Science. 190(5): 314-323.
[58] F.N. Tubiello, M. Salvatore, S. Rossi, A. Ferrara, N. Fitton, P. Smith. (2013). The FAOSTAT database of greenhouse gas emissions from agriculture. Environmental Research Letters. 8(1): 015009.
[59] C.-c. NING, P.-d. GAO, B.-q. WANG, W.-p. LIN, N.-h. JIANG, K.-z. CAI. (2017). Impacts of chemical fertilizer reduction and organic amendments supplementation on soil nutrient, enzyme activity and heavy metal content. Journal of Integrative Agriculture. 16(8): 1819-1831.
[60] L. Al Attar, M. Al-Oudat, K. Shamali, B. Abdul Ghany, S. Kanakri. (2012). Case study: heavy metals and fluoride contents in the materials of Syrian phosphate industry and in the vicinity of phosphogypsum piles. Environmental technology. 33(2): 143-152.
[61] E. Thomas, J. Omueti, O. Ogundayomi. (2012). The effect of phosphate fertilizer on heavy

metal in soils and Amaranthus caudatus. Agric. Biol. JN Am. 3(4): 145-149.
[62] S. Wu, B. Thapa, C. Rivera, Y. Yuan. (2021). Nitrate and nitrite fertilizer production from air and water by continuous flow liquid-phase plasma discharge. Journal of Environmental Chemical Engineering. 9(2): 104761.
[63] P.D. Gnanaprakasam, A.J. Vanisree. (2022). Recurring detrimental impact of agrochemicals on the ecosystem, and a glimpse of organic farming as a possible rescue. Environmental Science and Pollution Research. 29(50): 75103-75112.
[64] A. Shakoor, X. Chen, T.H. Farooq, U. Shahzad, F. Ashraf, A. Rehman, N.E. Sahar, W. Yan. (2020). Fluctuations in environmental pollutants and air quality during the lockdown in the USA and China: two sides of COVID-19 pandemic. Air Quality, Atmosphere & Health. 13: 1335-1342.
[65] E. Aguilera, P. Piñero, J. Infante Amate, M. González de Molina, L. Lassaletta, A. Sanz Cobeña. (2020). Emisiones de gases de efecto invernadero en el sistema agroalimentario y huella de carbono de la alimentación en España. Real Academia de Ingeniería: Madrid, Spain.
[66] H. Tian, R. Xu, J.G. Canadell, R.L. Thompson, W. Winiwarter, P. Suntharalingam, E.A. Davidson, P. Ciais, R.B. Jackson, G. Janssens-Maenhout. (2020). A comprehensive quantification of global nitrous oxide sources and sinks. Nature. 586(7828): 248-256.
[67] C. Qiao, L. Liu, S. Hu, J.E. Compton, T.L. Greaver, Q. Li. (2015). How inhibiting nitrification affects nitrogen cycle and reduces environmental impacts of anthropogenic nitrogen input. Global change biology. 21(3): 1249-1257.
[68] Z. Atafar, A. Mesdaghinia, J. Nouri, M. Homaee, M. Yunesian, M. Ahmadimoghaddam, A.H. Mahvi. (2010). Effect of fertilizer application on soil heavy metal concentration. Environmental monitoring and assessment. 160: 83-89.
[69] V. Natraj, D. Katyal. (2014). Study of Fertilizer Effect on soil status in and around Loni, Maharashtra, India. Applied Sciences, Engineering and Technology. 13: 188-192.
[70] N. Sharma, R. Singhvi. (2017). Effects of chemical fertilizers and pesticides on human health and environment: a review. International journal of agriculture, environment and biotechnology. 10(6): 675-680.
[71] J. Keuskamp, G. Van Drecht, A. Bouwman. (2012). European-scale modelling of groundwater denitrification and associated N2O production. Environmental pollution. 165: 67-76.
[72] Z. Nejatijahromi, H.R. Nassery, T. Hosono, M. Nakhaei, F. Alijani, A. Okumura. (2019). Groundwater nitrate contamination in an area using urban wastewaters for agricultural irrigation under arid climate condition, southeast of Tehran, Iran. Agricultural Water Management. 221: 397-414.
[73] P.M. Kopittke, E. Lombi, P. Wang, J.K. Schjoerring, S. Husted. (2019). Nanomaterials as fertilizers for improving plant mineral nutrition and environmental outcomes. Environmental Science: Nano. 6(12): 3513-3524.
[74] M. Körschens, E. Albert, M. Armbruster, D. Barkusky, M. Baumecker, L. Behle-Schalk, R. Bischoff, Z. Čergan, F. Ellmer, F. Herbst. (2013). Effect of mineral and organic fertilization on crop yield, nitrogen uptake, carbon and nitrogen balances, as well as soil organic carbon content and dynamics: results from 20 European long-term field experiments of the twenty-first century. Archives of Agronomy and Soil Science. 59(8): 1017-1040.
[75] K. Lubkowski. (2016). Environmental impact of fertilizer use and slow release of mineral nutrients as a response to this challenge. Polish Journal of Chemical Technology. 18(1): 72-79.
[76] L. Cao, F. Huang, I.Y. Massey, C. Wen, S. Zheng, S. Xu, F. Yang. (2019). Effects of microcystin-LR on the microstructure and inflammation-related factors of jejunum in mice. Toxins. 11(9): 482.
[77] C. Zhang, I.Y. Massey, Y. Liu, F. Huang, R. Gao, M. Ding, L. Xiang, C. He, J. Wei, Y. Li. (2019). Identification and characterization of a novel indigenous algicidal bacterium Chryseobacterium species against Microcystis aeruginosa. Journal of toxicology and environmental health, part A. 82(15): 845-853.
[78] J.R. Follett, R.F. Follett, W.C. Herz. (2010). Environmental and human impacts of reactive nitrogen. Advances in Nitrogen Management for Water Quality. 1-37.
[79] L. Mandic, D. Djukić, I. Beatovic, Z. Jovovic, M. Pesakovic, V. Stevovic. (2011). Effect of different fertilizers on the microbial activity and productivity of soil under potato cultivation. African Journal of Biotechnology. 10(36): 6954-6960.
[80] R.G. Joergensen, P. Mäder, A. Fließbach. (2010). Long-term effects of organic farming on fungal and bacterial residues in relation to microbial energy metabolism. Biology and fertility of soils. 46: 303-307.

[81] R. Murugan, S. Kumar. (2013). Influence of long-term fertilisation and crop rotation on changes in fungal and bacterial residues in a tropical rice-field soil. Biology and fertility of soils. 49: 847-856.

[82] R. Tao, Y. Liang, S.A. Wakelin, G. Chu. (2015). Supplementing chemical fertilizer with an organic component increases soil biological function and quality. Applied soil ecology. 96: 42-51.

[83] J. Eo, K.-C. Park. (2016). Long-term effects of imbalanced fertilization on the composition and diversity of soil bacterial community. Agriculture, Ecosystems & Environment. 231: 176-182.

[84] D. Francioli, E. Schulz, G. Lentendu, T. Wubet, F. Buscot, T. Reitz. (2016). Mineral vs. organic amendments: microbial community structure, activity and abundance of agriculturally relevant microbes are driven by long-term fertilization strategies. Frontiers in Microbiology. 7: 1446.

[85] R. Sun, X. Guo, D. Wang, H. Chu. (2015). Effects of long-term application of chemical and organic fertilizers on the abundance of microbial communities involved in the nitrogen cycle. Applied soil ecology. 95: 171-178.

[86] M. Schloter, P. Nannipieri, S.J. Sørensen, J.D. van Elsas. (2018). Microbial indicators for soil quality. Biology and fertility of soils. 54: 1-10.

[87] P. Nannipieri, C. Trasar-Cepeda, R.P. Dick. (2018). Soil enzyme activity: a brief history and biochemistry as a basis for appropriate interpretations and meta-analysis. Biology and fertility of soils. 54: 11-19.

[88] P. Luo, X. Han, Y. Wang, M. Han, H. Shi, N. Liu, H. Bai. (2015). Influence of long-term fertilization on soil microbial biomass, dehydrogenase activity, and bacterial and fungal community structure in a brown soil of northeast China. Annals of microbiology. 65(1): 533-542.

[89] C. Ma, J. Wu, F. Li. (2022). Impacts of combined water-saving irrigation and controlled-release urea on CH4 emission and its associated microbial communities and function. Science of the Total Environment. 830: 154724.

[90] G. Luo, V.-P. Friman, H. Chen, M. Liu, M. Wang, S. Guo, N. Ling, Q. Shen. (2018). Long-term fertilization regimes drive the abundance and composition of N-cycling-related prokaryotic groups via soil particle-size differentiation. Soil Biology and Biochemistry. 116: 213-223.

[91] W. Zou, M. Lang, L. Zhang, B. Liu, X. Chen. (2022). Ammonia-oxidizing bacteria rather than ammonia-oxidizing archaea dominate nitrification in a nitrogen-fertilized calcareous soil. Science of the Total Environment. 811: 151402.

[92] Y. Ouyang, J.R. Reeve, J.M. Norton. (2018). Soil enzyme activities and abundance of microbial functional genes involved in nitrogen transformations in an organic farming system. Biology and fertility of soils. 54: 437-450.

[93] R. Tao, S.A. Wakelin, Y. Liang, G. Chu. (2017). Response of ammonia-oxidizing archaea and bacteria in calcareous soil to mineral and organic fertilizer application and their relative contribution to nitrification. Soil Biology and Biochemistry. 114: 20-30.

[94] F. Cai, P. Luo, J. Yang, M. Irfan, S. Zhang, N. An, J. Dai, X. Han. (2021). Effect of long-term fertilization on ammonia-oxidizing microorganisms and nitrification in brown soil of Northeast China. Frontiers in Microbiology. 11: 622454.

[95] X. Chen, L.-M. Zhang, J.-P. Shen, W.-X. Wei, J.-Z. He. (2011). Abundance and community structure of ammonia-oxidizing archaea and bacteria in an acid paddy soil. Biology and fertility of soils. 47: 323-331.

[96] A. Ghaly, V. Ramakrishnan. (2015). Nitrogen sources and cycling in the ecosystem and its role in air, water and soil pollution: A critical review. Journal of Pollution Effects & Control. 3(2): 1-26.

[97] J. Zhao, T. Ni, J. Li, Q. Lu, Z. Fang, Q. Huang, R. Zhang, R. Li, B. Shen, Q. Shen. (2016). Effects of organic–inorganic compound fertilizer with reduced chemical fertilizer application on crop yields, soil biological activity and bacterial community structure in a rice–wheat cropping system. Applied soil ecology. 99: 1-12.

[98] V.C. Pankievicz, F.P. do Amaral, K.F. Santos, B. Agtuca, Y. Xu, M.J. Schueller, A.C.M. Arisi, M.B. Steffens, E.M. de Souza, F.O. Pedrosa. (2015). Robust biological nitrogen fixation in a model grass–bacterial association. The Plant Journal. 81(6): 907-919.

[99] J.I. Prosser, G.W. Nicol. (2012). Archaeal and bacterial ammonia-oxidisers in soil: the quest for niche specialisation and differentiation. Trends in microbiology. 20(11): 523-531.

[100] T.E. Koper, J.M. Stark, M.Y. Habteselassie, J.M. Norton. (2010). Nitrification exhibits Haldane kinetics in an agricultural soil treated with ammonium sulfate or dairy-waste compost. FEMS microbiology ecology. 74(2): 316-322.

[101] C. Ai, G. Liang, J. Sun, X. Wang, P. He, W. Zhou. (2013). Different roles of rhizosphere

effect and long-term fertilization in the activity and community structure of ammonia oxidizers in a calcareous fluvo-aquic soil. Soil Biology and Biochemistry. 57: 30-42.
[102] J. Tian, F. Ge, D. Zhang, S. Deng, X. Liu. (2021). Roles of phosphate solubilizing microorganisms from managing soil phosphorus deficiency to mediating biogeochemical P cycle. Biology. 10(2): 158.
[103] Z. Yuan, S. Jiang, H. Sheng, X. Liu, H. Hua, X. Liu, Y. Zhang. (2018). Human perturbation of the global phosphorus cycle: changes and consequences. Environmental science & technology. 52(5): 2438-2450.
[104] A. Onet, L.C. Dincă, P. Grenni, V. Laslo, A.C. Teusdea, D.L. Vasile, R.E. Enescu, V.E. Crisan. (2019). Biological indicators for evaluating soil quality improvement in a soil degraded by erosion processes. Journal of Soils and Sediments. 19: 2393-2404.
[105] A. Ashworth, J. DeBruyn, F. Allen, M. Radosevich, P. Owens. (2017). Microbial community structure is affected by cropping sequences and poultry litter under long-term no-tillage. Soil Biology and Biochemistry. 114: 210-219.
[106] X. Cui, Y. Zhang, J. Gao, F. Peng, P. Gao. (2018). Long-term combined application of manure and chemical fertilizer sustained higher nutrient status and rhizospheric bacterial diversity in reddish paddy soil of Central South China. Scientific reports. 8(1): 16554.
[107] F. Wang, W. Han, S. Chen, W. Dong, M. Qiao, C. Hu, B. Liu. (2020). Fifteen-year application of manure and chemical fertilizers differently impacts soil ARGs and microbial community structure. Frontiers in Microbiology. 11: 62.
[108] F. Morari, G. Vellidis, P. Gay. (2011). Nitrogen Cycle, Fertilizers, and N Loss Pathways.
[109] E. Elka, F. Laekemariam. (2020). Effects of organic nutrient sources and NPS fertilizer on the agronomic and economic performance of haricot bean (Phaseolus vulgaris L.) in Southern Ethiopia. Applied and Environmental Soil Science. 2020: 1-9.
[110] J. Nyamangara, J. Kodzwa, E.N. Masvaya, G. Soropa, The role of synthetic fertilizers in enhancing ecosystem services in crop production systems in developing countries. In *The role of ecosystem services in sustainable food systems*, Elsevier: 2020; pp 95-117.
[111] Z. Song, H. Gao, P. Zhu, C. Peng, A. Deng, C. Zheng, M.A. Mannaf, M.N. Islam, W. Zhang. (2015). Organic amendments increase corn yield by enhancing soil resilience to climate change. The Crop Journal. 3(2): 110-117.
[112] H. Ali, E. Khan, I. Ilahi. (2019). Environmental chemistry and ecotoxicology of hazardous heavy metals: environmental persistence, toxicity, and bioaccumulation. Journal of chemistry. 2019.
[113] X. Zhang, L. Yan, J. Liu, Z. Zhang, C. Tan. (2019). Removal of different kinds of heavy metals by novel PPG-nZVI beads and their application in simulated stormwater infiltration facility. Applied Sciences. 9(20): 4213.
[114] X.-X. Chen, Y.-M. Liu, Q.-Y. Zhao, W.-Q. Cao, X.-P. Chen, C.-Q. Zou. (2020). Health risk assessment associated with heavy metal accumulation in wheat after long-term phosphorus fertilizer application. Environmental pollution. 262: 114348.
[115] C. Su. (2014). A review on heavy metal contamination in the soil worldwide: Situation, impact and remediation techniques. Environmental Skeptics and Critics. 3(2): 24.
[116] A. Branzini, M.S. Zubillaga. (2012). Comparative use of soil organic and inorganic amendments in heavy metals stabilization. Applied and Environmental Soil Science. 2012.
[117] W. Xiaobing, L. Wuxing, L. Zhengao, T. Ying, P. Christie, L. Yongming. (2020). Effects of long-term fertilizer applications on peanut yield and quality and plant and soil heavy metal accumulation. Pedosphere. 30(4): 555-562.
[118] P. Ai, K. Jin, A. Alengebawy, M. Elsayed, L. Meng, M. Chen, Y. Ran. (2020). Effect of application of different biogas fertilizer on eggplant production: Analysis of fertilizer value and risk assessment. Environmental Technology & Innovation. 19: 101019.
[119] B.V. Tangahu, S.R. Sheikh Abdullah, H. Basri, M. Idris, N. Anuar, M. Mukhlisin. (2011). A review on heavy metals (As, Pb, and Hg) uptake by plants through phytoremediation. International journal of chemical engineering. 2011.
[120] A. Asati, M. Pichhode, K. Nikhil. (2016). Effect of heavy metals on plants: an overview. International Journal of Application or Innovation in Engineering & Management. 5(3): 56-66.
[121] P. Vejan, T. Khadiran, R. Abdullah, N. Ahmad. (2021). Controlled release fertilizer: A review on developments, applications and potential in agriculture. Journal of Controlled Release. 339: 321-334.
[122] J. Chen, S. Lü, Z. Zhang, X. Zhao, X. Li, P. Ning, M. Liu. (2018). Environmentally friendly fertilizers: A review of materials used and their effects on the environment. Science of the Total Environment. 613: 829-839.

[123] Y. Wei, J. Li, Y. Li, B. Zhao, L. Zhang, X. Yang, J. Chang. (2017). Research on permeability coefficient of a polyethylene controlled-release film coating for urea and relevant nutrient release pathways. Polymer Testing. 59: 90-98.

[124] M.H. Rahman, K.S. Haque, M.Z.H. Khan. (2021). A review on application of controlled released fertilizers influencing the sustainable agricultural production: A Cleaner production process. Environmental Technology & Innovation. 23: 101697.

[125] M. Kalwani, H. Chakdar, A. Srivastava, S. Pabbi, P. Shukla. (2022). Effects of nanofertilizers on soil and plant-associated microbial communities: Emerging trends and perspectives. Chemosphere. 287: 132107.

[126] T. Gomiero, D. Pimentel, M.G. Paoletti. (2011). Environmental impact of different agricultural management practices: conventional vs. organic agriculture. Critical Reviews in Plant Sciences. 30(1-2): 95-124.

[127] S. Siddique, M. Hamid, A. Tariq, A.G. Kazi. (2014). Organic farming: the return to nature. Improvement of Crops in the Era of Climatic Changes: Volume 2. 249-281.

[128] T. Gomiero, Organic agriculture: impact on the environment and food quality. In *Environmental impact of agro-food industry and food consumption*, Elsevier: 2021; pp 31-58.