*The Future of Agriculture*

FSA

***Article***

# Harmful Effects of Chemical Fertilizers on Living Organisms and the Environment (Review)

**Nahla Salim Hammok**

Environmental Researches Center, University of Mosul, Iraq

https://doi.org/10.37229/fsa.fjh.2025.08.24

***Corresponding author:** hammok2019@uomosul.edu.iq

CrossMark

**Future Science Association**

**Available online free at**
www.futurejournals.org

**Print ISSN:** 2687-8151
**Online ISSN:** 2687-8216

**Received:** 1 July 2024
**Accepted:** 10 August 2024
**Published:** 24 August 2025

**Publisher's Note:** FA stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



**Abstract**: Throughout the past decades, the massive application of chemical fertilizers has progressed to stratospheric proportions that have caused serious ecological and health effects to people. This overview employs a strict assessment of the complex negative impacts of these chemicals in the land and water ecosystem. There is specific emphasis on the evolution of soil acidity, impairment of microbial diversity, augmentation of osmotic stress and salinity. Nitrogen has been applied at an accelerated rate, which has led to significant rates of leaching of nitrates and contamination of the ground waters, hence, the eutrophication and poor quality of waters. Such phenomenon degrade aquatic environments and ecological structure of foods webs. More so, the excess of nitrogen generates oxidative stress and metabolic imbalances of aquatic organisms, in particular fish. At the same time, the bioaccumulation of harmful substances and excessive concentration of heavy metals, cadmium and lead in soils and crops increase the threats to the health and human and ecosystem integrity. Prolonged application of chemical fertilizers also changes the biogeochemical cycles, intensifies the toxicity of the ecology and deteriorates the overall stability of the environment. The evidence presented in the current paper highlights the necessity of undertaking a critical examination of the current method of agricultural production that involves fertilizers underlining the extent and depth of their adverse impacts on environment and biology.

**Key words**: Harmful effects of chemical fertilizers, Microbial biodiversity loss, Heavy metal accumulation, Bioaccumulation

# التأثيرات الضارة للأسمدة الكيميائية على الكائنات الحية والبيئة

نهلة سالم حموك

مركزبحوث البيئة /جامعة الموصل

**الخلاصة**

شهدت العقود الأخيرة تصاعدًا ملحوظًا في استخدام الأسمدة الكيميائية ضمن الممارسات الزراعية المكثفة، مما أسفر عن آثار بيئية وصحية عميقة ومركبة. وتهدف هذه المراجعة إلى تحليل الأضرار الناجمة عن هذه المواد على الأنظمة البيئية الأرضية والمائية. تشمل هذه الأضرار ارتفاع حموضة التربة، واضطراب التنوع الميكروبي، وتفاقم الإجهاد التناضحي والملوحة، مما يؤدي إلى تدهور الخصائص الحيوية للتربة وخلل في توازنها البيئي. كما يسهم الإفراط في استخدام الأسمدة النيتروجينية في تسرب النترات إلى المياه الجوفية، وتلويثها، وتحفيز عمليات التخنث في البيئات المائية، مما يؤدي إلى الإضرار بالنظم الإيكولوجية وتدهور جودة المياه. ويمتد التأثير إلى الكائنات المائية، حيث يسبب النيتروجين الزائد إجهادًا تأكسديًا واضطرابات أيضية، خصوصًا لدى الأسماك. كذلك، يؤدي التراكم الأحيائي للملوثات وتراكم المعادن الثقيلة مثل الكادميوم والرصاص في التربة والنباتات إلى تهديدات خطيرة على الصحة العامة وسلامة الغذاء. وتشير الأدلة إلى أن الاستخدام طويل الأمد للأسمدة الكيميائية يسبب اختلالًا في الدورات البيوجيوكيميائية، ويزيد من السمية البيئية، مما يُضعف الاستقرار البيئي العام. وعليه، تبرز هذه المراجعة الحاجة المُلِحّة إلى تقييم علمي دقيق لمخاطر الاعتماد المتزايد على الأسمدة الكيميائية، في ظل تداعياتها المتزايدة على البيئة وصحة الإنسان.

## 1. Introduction

The widespread adoption of chemical fertilizers in the 20th century transformed global agriculture, enabling remarkable gains in crop productivity and food security. Innovations such as the Haber–Bosch process, which enabled industrial-scale nitrogen fixation, have been foundational to this transformation(Erisman et al., 2008) . Synthetic nitrogen (N), phosphorus (P), and potassium (K) fertilizers have helped increase global cereal yields by over 200% since the 1930s **(Tilman et al., 2002; Zhang et al., 2015)**, supporting a population that has more than quadrupled since the early 20th century. However, as the reviewed article emphasizes, these productivity gains have come at significant ecological cost. A growing body of research now identifies chemical fertilizers as major contributors to environmental degradation—implicating them in soil nutrient imbalance, groundwater contamination, biodiversity loss, and greenhouse gas emissions**(Devi et al., 2025; Salem et al., 2020; Steffen et al., 2015)** . Globally, more than 70% of applied nitrogen and up to 60% of phosphorus fail to be absorbed by crops, instead leaching into surrounding ecosystems**(Bouwman et al., 2013)** , where they disrupt biogeochemical cycles and accumulate as pollutants.

This review synthesizes evidence from recent studies to examine the multidimensional impacts of chemical fertilizers on soil health, aquatic ecosystems, terrestrial and aquatic organisms, and climate systems. We further evaluate sustainable alternatives and broader policy frameworks aimed at balancing agricultural productivity with long-term environmental sustainability and planetary health **(Hossain et al., 2022; Rockström et al., 2009; Zhang et al., 2015).** Understanding these complex interactions is essential to shaping agricultural practices that are both productive and ecologically resilient.

### Impact of Chemical Fertilizers on Soil Health and Microbial Communities: An Integrated Analysis

Long-term use of chemical fertilizers initiates cascading soil degradation through physicochemical and biological mechanisms, undermining soil functions, reducing crop productivity, and threatening sustainable agriculture.

### Soil Acidification and Nutrient Imbalance

One of the most immediate effects of synthetic nitrogen fertilizers—particularly urea and ammonium sulfate—is soil acidification. During nitrification, hydrogen ions ($H^+$) are released, lowering soil pH over time. In intensively managed fields, pH levels can decline by 1.5–2.0 units over a decade, often falling below 5.5—thresholds that mobilize phytotoxic ions like aluminum ($Al^{3+}$) and manganese ($Mn^{2+}$), damaging roots and locking essential nutrients like phosphorus into unavailable forms **(JianHua et al., 2024; Wang et al., 2018)**. As illustrated in Figure 1, the acidification cascade begins with the biological conversion of ammonium to nitrate, producing surplus $H^+$ ions that accumulate in the rhizosphere. In acidic soils (pH < 5.5), this drop in pH solubilizes toxic metals such as aluminum ($Al^{3+}$) and manganese ($Mn^{2+}$), which interfere with root development and restrict phosphorus availability by promoting its fixation with iron and aluminum oxides. These chemical shifts impair nutrient uptake even when fertilizer rates remain constant, creating a hidden form of yield loss over time.

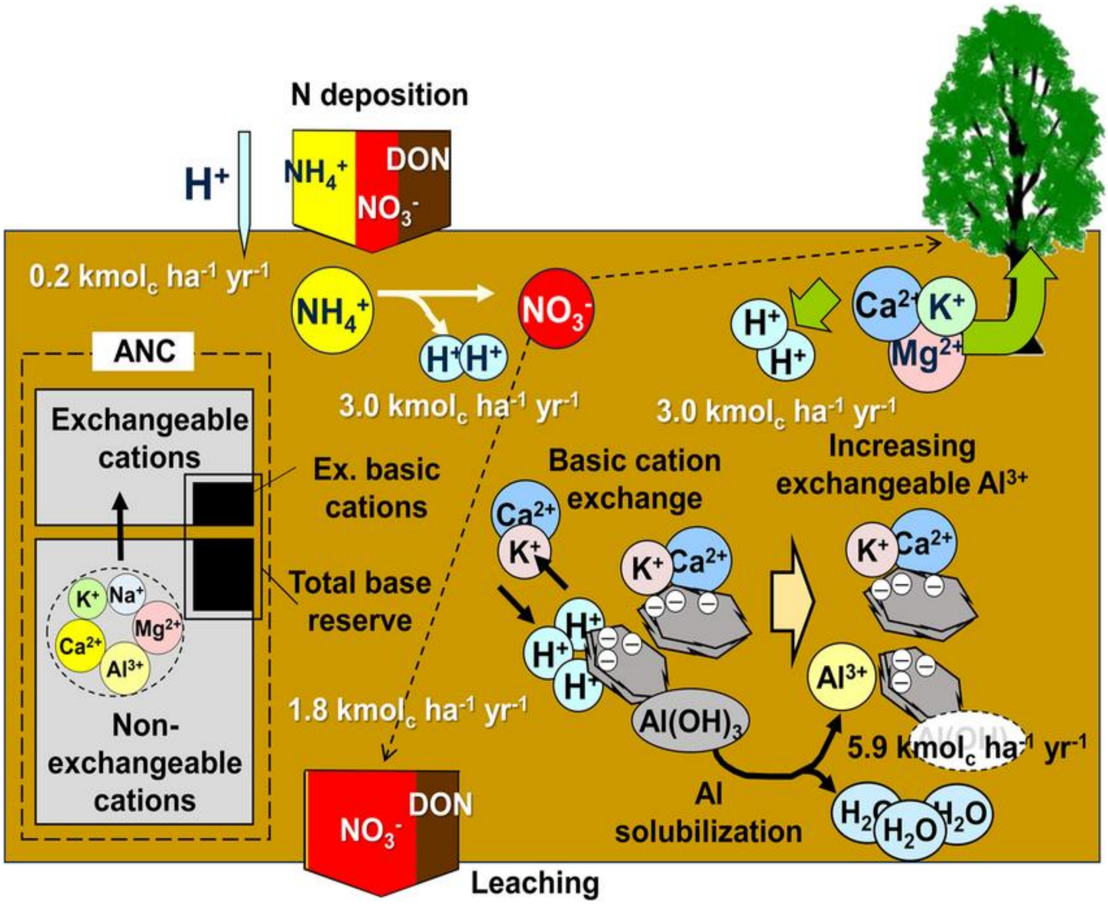


Figure 1. Soil Acidification by Ammonium Fertilizers **(Fujii et al., 2024)**

A 33-year field experiment in China demonstrated that soil pH decreased significantly (up to 1.19 units) under balanced NPK fertilization in the 0–20 cm soil layer, with acidification depth reaching 40 cm. Exchangeable acidity and aluminum increased by over 100%, while base saturation declined by up to 15 percentage points, indicating severe acidification and nutrient imbalance**(JianHua et al., 2024)** .

### Microbial Diversity Suppression

Against this backdrop of constant usage of chemical fertilizers, significant impacts are felt on the diversity and the structure of soil microbial communities. A pattern of repeated application of nitrogen and phosphorus fertilizers brought about a noticeable change in the structure of bacterial communities in the paddy fields **(Iqbal et al., 2022)**. Figure 2 depicts the resulting pattern as a high level of clustering in the chemically fertilized plots on a Principal Coordinate Analysis (PCoA) plot, clear distinction between them and the organic or integrated amendment plots.

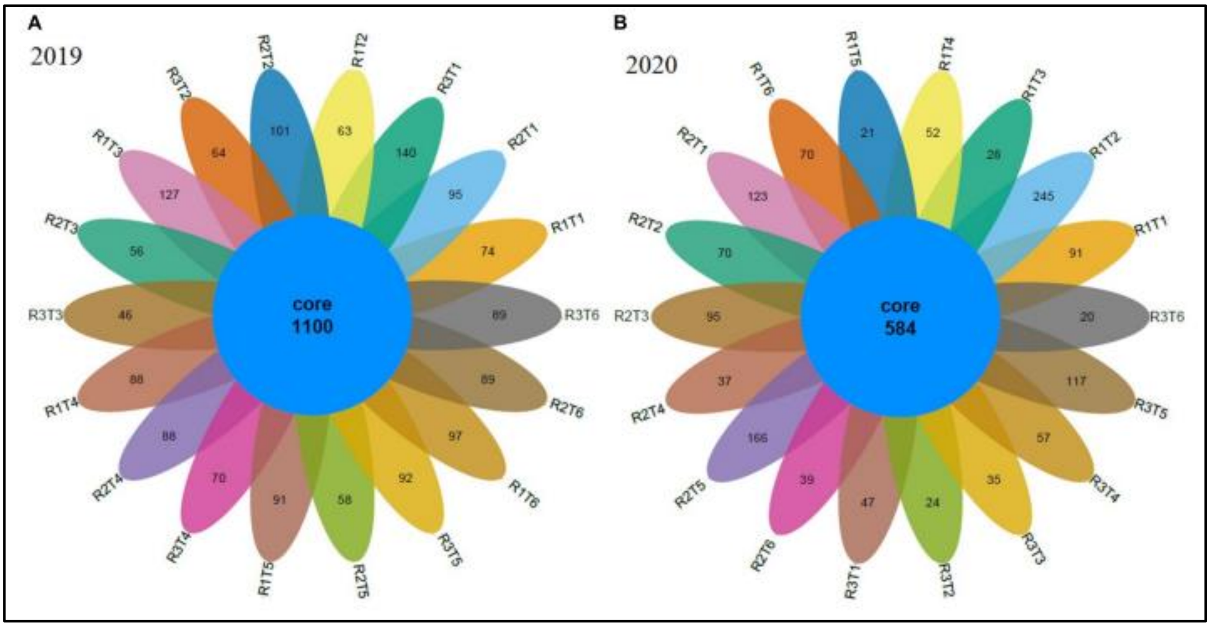


Figure 2: Venn diagrams of distribution of operational taxonomic units (OTUs) implemented in the different organic and inorganic fertilizing regimes in the 2019(A) and 2020(B) years. The number of OTUs unique to a specific treatment is represented by a pentagon, whereas the blue core contains those shared by all the treatments, namely OTUs occurring every year (1,100 OTUs in 2019, 584 in 2020). Adapted from **(Iqbal et al., 2022)**.

The results also indicate that chemical fertilizer significantly prefers a community which includes a small suite of opportunistic phyla of bacteria, which decreases community evenness and richness compared with the treatments using organic sources of nutrient as shown in Figure 3.

Taken together, these findings provide unambiguous data that repeated use of chemical fertilizers inhibits the microbial diversity and disdains the community balance to enrich a limited taxonomic cadre.

### Effects of Osmotic Stress and Salinity on Microbial Communities

The application of chemical fertilizers in excess can be used to enhanced salinity on the soil and in result, has an effect on raising electrical conductivity and this in turn has an osmotic effect that is very harmful on the microbial communities that exist in soil. These effects were indeed verified in the study by Chang et al. (2021), which also reported remarkable effects of soil salinity, with electrical conductivities (EC) of 0.36-6.72 ds/m at different salinization gradients. The soil organic carbon (SOC), available nitrogen (AN), available phosphorus (AP) and available potassium (AK) that are the key soil biochemical indicators showed a steep decrease as the salinity increased. Increased salinity also significantly repressed the enzyme activities associated with nutrient cycling such as alkaline phosphatase, invertase, urease and catalase (Table 1)**(Hou et al., 2021)**.

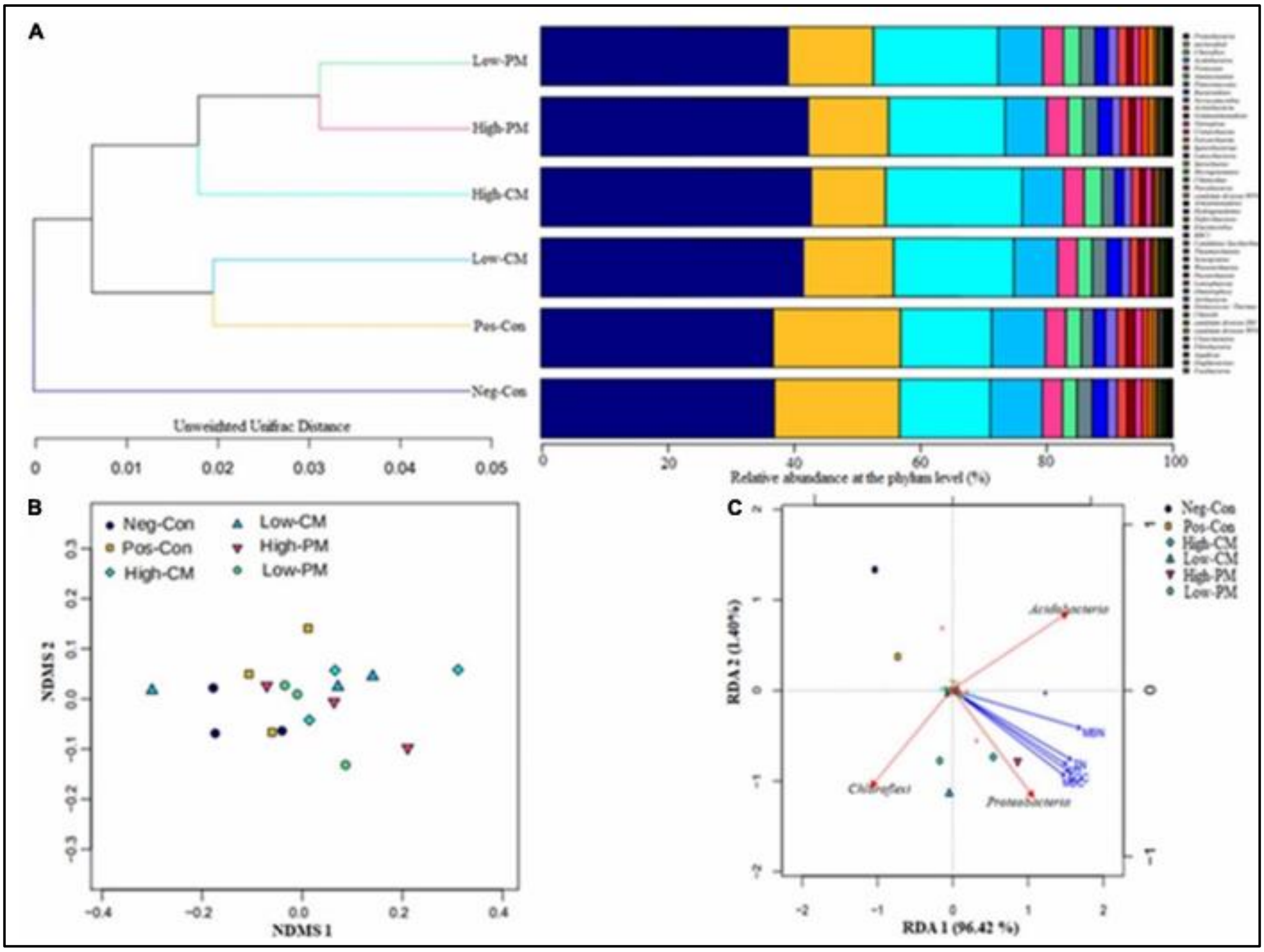


Figure 3. Chemical fertiliser effect on phylum-level relative abundance profiles and bacterial group dominance **(Iqbal et al., 2022)**.

**Table (1). A high salinity is inversely related to soil organic carbon (SOC), availability of nutrients and enzyme activity which is critical to microbial activity and all over soil health. Adapted from (14)**

| Physicochemical Factor | S1 | | S2 | | S3 | |
|---|---|---|---|---|---|---|
| | S1_RS | S1_BS | S2_RS | S2_BS | S3_RS | S3_BS |
| $EC_e$ (ds/m) | 0.34 ± 0.01 [c] | 0.36 ± 0.03 [c] | 3.24 ± 0.39 [b] | 3.69 ± 0.11 [b] | 6.13 ± 0.72 [a] | 6.72 ± 0.49 [a] |
| pH | 7.88 ± 0.07 [c] | 7.99 ± 0.07 [bc] | 8.16 ± 0.04 [bc] | 8.23 ± 0.04 [b] | 8.32 ± 0.23 [ab] | 8.58 ± 0.29 [a] |
| clay content (%) | 0.55 ± 0.23 [a] | 0.57 ± 0.12 [a] | 0.53 ± 0.19 [a] | 0.67 ± 0.10 [a] | 0.90 ± 0.67 [a] | 0.61 ± 0.03 [a] |
| silt content (%) | 26.72 ± 2.88 [a] | 25.69 ± 1.57 [a] | 30.91 ± 2.15 [a] | 33.09 ± 1.37 [a] | 32.47 ± 9.25 [a] | 30.95 ± 2.70 [a] |
| sand content (%) | 72.73 ± 3.10 [a] | 73.74 ± 1.67 [a] | 68.56 ± 2.30 [a] | 66.24 ± 1.47 [a] | 66.63 ± 9.92 [a] | 68.44 ± 2.73 [a] |
| $K^+$ (mg/kg) | 24.00 ± 2.29 [e] | 41.5 ± 2.18 [d] | 63.67 ± 12.75 [c] | 76.50 ± 6.38 [b] | 67.33 ± 5.84 [bc] | 123.83 ± 1.04 [a] |
| $Na^+$ (mg/kg) | 27.00 ± 2.29 [e] | 97.33 ± 3.75 [e] | 271.00 ± 36.17 [d] | 2890.00 ± 193.08 [b] | 652.67 ± 37.44 [c] | 3334.67 ± 63.49 [a] |
| $Ca^{2+}$ (mg/kg) | 158.20 ± 5.78 [d] | 151.64 ± 2.73 [d] | 495.75 ± 18.43 [c] | 1132.00 ± 131.76 [b] | 2101.50 ± 361.50 [a] | 2193.50 ± 161.47 [a] |
| $Mg^{2+}$ (mg/kg) | 4.19 ± 0.92 [d] | 5.71 ± 1.82 [d] | 261.00 ± 24.98 [c] | 715.42 ± 65.67 [b] | 271.08 ± 94.11 [c] | 1582.50 ± 68.27 [a] |
| SOC (g/kg) | 12.61 ± 0.20 [a] | 11.23 ± 0.77 [b] | 6.29 ± 0.46 [c] | 6.20 ± 1.11 [c] | 5.49 ± 0.20 [c] | 5.67 ± 0.11 [c] |
| AN (mg/kg) | 28.24 ± 2.46 [a] | 30.57 ± 4.20 [a] | 20.54 ± 2.14 [bc] | 22.40 ± 4.28 [b] | 16.34 ± 1.07 [c] | 18.90 ± 2.14 [bc] |
| AP (mg/kg) | 60.33 ± 3.13 [a] | 62.07 ± 1.46 [a] | 52.00 ± 3.51 [b] | 50.17 ± 2.37 [b] | 25.33 ± 1.92 [d] | 34.70 ± 2.01 [c] |
| AK (mg/kg) | 242.67 ± 9.71 [a] | 242.00 ± 21.52 [a] | 142.33 ± 7.77 [c] | 205.33 ± 13.50 [b] | 109.67 ± 5.86 [d] | 98.33 ± 2.89 [d] |
| ALP (mg/g/d) | 3.19 ± 0.20 [a] | 3.49 ± 0.37 [a] | 1.43 ± 0.06 [b] | 0.88 ± 0.18 [c] | 0.69 ± 0.06 [cd] | 0.42 ± 0.02 [d] |
| Invertase (mg/g/d) | 12.36 ± 1.25 [a] | 10.97 ± 1.01 [b] | 4.31 ± 0.32 [c] | 3.24 ± 0.29 [c] | 1.46 ± 0.04 [d] | 1.07 ± 0.14 [d] |
| Urease (mg/g/d) | 1.57 ± 0.09 [a] | 1.63 ± 0.02 [a] | 0.87 ± 0.06 [b] | 0.75 ± 0.04 [c] | 0.49 ± 0.02 [b] | 0.42 ± 0.01 [d] |
| CAT (mL/g) | 1.47 ± 0.12 [a] | 1.10 ± 0.06 [b] | 1.00 ± 0.03 [bc] | 0.94 ± 0.06 [c] | 0.85 ± 0.02 [cd] | 0.80 ± 0.02 [d] |

The unfavorable effect of salinity on microbial metabolism and the consequent biochemical processes in the soil is emphasized by reductions in the activity of microbial enzymes. Microbial growth, diversity and community structure is hampered by such salt-mediated osmotic stresses and ion toxicity leading to impaired soil fertility and consequent failure to ensure sustainable agricultural productivity **(Hou et al., 2021; Niu et al., 2021)**.

**Ecological and Functional Effects**

In the long run, overuse of chemical fertilizer reduces the soil microbial diversity and affects unfavorably microbial activity, soil organic matter, stable aggregates, and nutrient cycling. These are the adverse effects that stimulate soil acidity and salinity, hence reducing the capacity of the soil by increasing the capacity of soil erosion**(Jote, 2023; Pahalvi et al., 2021)**. Acidification of soils inhibits accessibility of nutrients and the activities of microbes, as osmotic stress caused by salinity limits the activity of enzymes and microorganisms. A decline in microbial activity is a self-reinforcing feedback, preferably directed to a decrease of soil organic carbon and fertility and an increase in the use of synthetic fertilizers. Moreover, with excessive use of chemical fertilizers, there are the chances of build up of toxic elements which reduce the quality of soil and food and reduce the beneficial microbe population hence weaken the inherent disease suppression and nutrient cycling**(Jote, 2023)**. Therefore, the combination of chemical fertilizer application with the use of organic amendments is crucial to protect the health of the soil to promote prolonged sustainability of agricultural farming.

**Eutrophication water pollution**

There are dire hydrological effects of agricultural intensification via use of chemical fertilizers. Fertilizer runoff of nutrients, mostly nitrogen (N) and phosphorus (P), on fertilized land is now commonly recognized as a major source of eutrophication in both freshwater and maritime ecosystems. This process induces harmful algal blooms, hypoxia and extensive ecological impact on the aquatic life.

**Nitrate leaching and nutrient runoff**

Excessive use of N fertilizer in the agricultural systems has been common leading to overloading of use by the crops and thus the nitrogen usually leaches to flow into the ground and the surface water. In their work, Gonzalez-Yajimovich et al. (2024) revealed that the average concentration of nitrate in agricultural drainage was nearly 34 mg/L, and some of the values had exceeded standards established by environmental authorities**(Adebanjo-Aina and Oludoye, 2025)**. This widespread contamination of nitrate is quite dangerous both to the aquatic life and also to human life especially in the areas that lack any control measures. The soil attributes, agricultural practices and the conditions prevailing within the environment balance the variability in nitrate concentrations which conveys the fact that nutrient runoff in the agriculture production system is indeed a multifactorial process **(Huang et al., 2017).**

**Nitrogen Fertiliser Rates and Eutrophication**

Since the 1980s, anthropogenic fertilizer use of nitrogen in Taihu Lake Basin has been on the increase, leading to dramatic increases in nitrogen runoff and leaching and eutrophication. According to Diao et al. (2020), fertilization rates rose to around 600 kg N/ha/year compared to about 350-kg N/ha/year and the biggest loss of nitrogen was registered in the late 1990s. The amount of inputs that was beyond 500 kg N/ha/year did not contribute significantly to crop yields but were associated with the increase in nitrogen pollution. The authors, thus, come to a conclusion that the more accurate control of nitrogen fertilizers is both possible and needed. Their study is able to tie higher nitrogen input to the eutrophic situation in the basin in Table 2 through historical applications of fertilizers, and subsequent water-quality trends**(Diao et al., 2020)**.

**Table (2). Taihu Lake water quality and eutrophic status variations due to nitrogen fertiliser application. Adapted from (20)**

| Period | Fertilizer Rate (kg N·ha$^{-1}$·year$^{-1}$) | Water Quality | Eutrophication Level |
|---|---|---|---|
| 1950s | <100 | <0.54–0.58 mg·L$^{-1}$ [51] | Oligotrophic |
| Around the 1980s | <354 | 0.9–2.57 mg·L$^{-1}$, average 1.54 mg·L$^{-1}$ | Mesotrophic |
| Around the 1990s | 440–584 | 1.47–1.83 mg·L$^{-1}$ in 1987–1988 [52]; 1.73–2.87 mg·L$^{-1}$ in 1992–1994 [53] | Mesotrophic-Eutrophic |
| Around the 2000s | 586–640 | >2.5 mg·L$^{-1}$ [48] | Eutrophic |
| After 2000 | 513–560 | Average 2.34 mg·L$^{-1}$ (1.92–2.72 mg·L$^{-1}$) during 2002–2006 [50] | Eutrophic |

Although Hina (2024) claims that nitrogen leaching is condition-dependent and crop-specific, a meta-analysis by the author conducted over a period of 39 years points to an opposite effect. Leaching responses vary with soil texture, fertilizer source and management practices and at times organic fertilizers have been shown to have a greater or equal nitrate loss than synthetic fertilizer. These findings support the need to have moderated fertilization plans to achieve the goals of protecting the water quality and augment agricultural sustenance **(Hina, 2024)**.

### Ecological Effects and Nutrient Trends

Fertilization of nitrogen on a large scale on the Yangtze Plain and the Taihu Lake Basin has expanded high nitrogen leaching and runoff that has enhanced eutrophication and has reduced the quality of water. Guan et al. (2023) showed that NUE decreased, starting with 50 % in the year 1979 to 25 % in 2018, coupled with quantifiable N leaching to lakes**(Guan et al., 2023)**. The researchers also indicated that eutrophication trends in over 50 lakes were co-related significantly with nutrient inputs that are contributed by both agriculture and industry. Diao et al. (2020) published a parallel study showing that nitrogen losses based on the Taihu rice-wheat system increased between the 1980s and the late 1990s as fertilizer rates rose to 350, 600 kg N/ha/year, and there was no significant increase in yields after the application of fertilizer exceeded 500 kg N/ha/year, though nitrogen exports increased, especially during rainy periods. Taken together, these results reaffirm the need of optimized nutrient management specific to regions that will reduce environmental effects without diminishing agricultural productivity **(Diao et al., 2020)**.

### Terrestrial and aquatic toxicity

Chemical fertilizers have acute and chronic toxic effects on the terrestrial and aquatic life. The effects are associated with a direct contact with ammonia, nitrate, and metal residues, which result in oxidative stress, bioaccumulation, suppression of the immune system and organ disintegration.

### Aquatic Toxicity: Oxidative Damage and Ammonia Stress in Fish

Freshwater life is extremely intolerant to un-ionized ammonia (NH 3), which is often released by ammonium-based fertilizers (urea among others). Researchers in the study by **Xu et al. (2021)**

considered the sublethal effects of ammonia on Carassius auratus (crucian carp) in fluid that simulated fertilizer runoffs. According to their histopathological analyses, pictured in Figure 4 **(Xu et al., 2021)**, considerable tissue damage was observed in the gills and liver with necrosis, epithelial lifting, and congestion in the vascular system, putting the efficiency of respiration and the operation of detoxification liver functions at risk **(Xu et al., 2021)**.

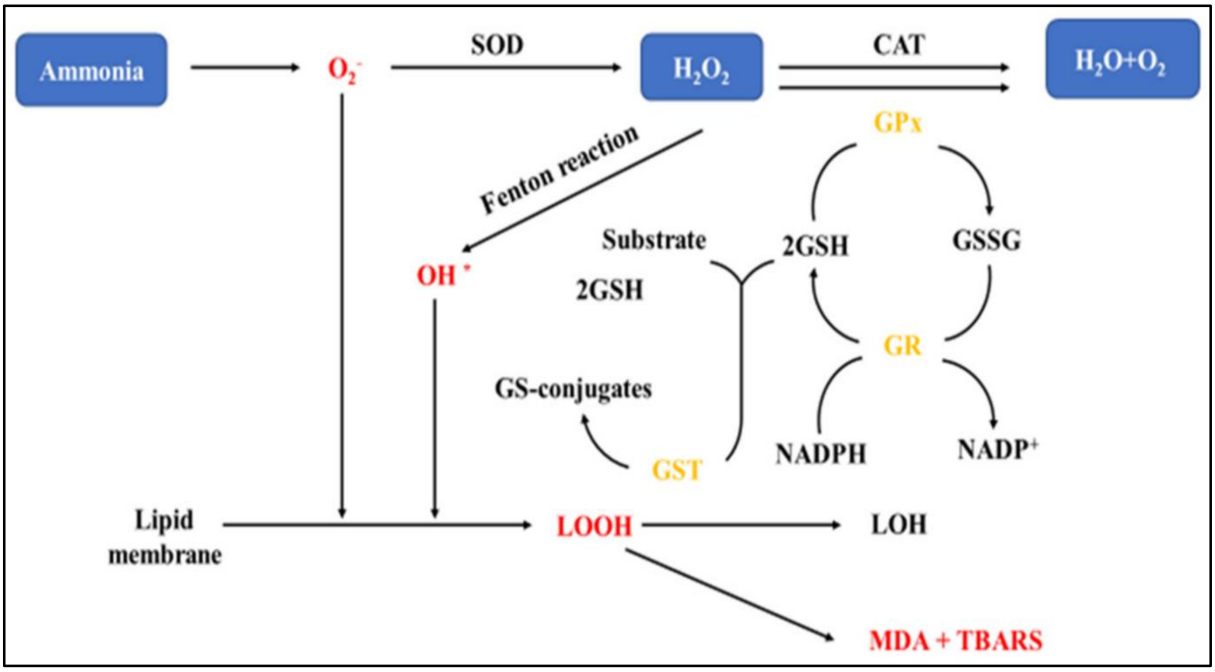


Figure 4. Necrosis, epithelial lifting, and vascular congestion in ammonia-exposed Carassius auratus gill and liver tissues (23).

The Ammonia toxicity in fish occurs in several ways leading to perturbations of the hematological parameters, generation of oxidative stress due to the imbalance of antioxidants, alteration of the immune status, and neurotoxicity. Due to the fact that fish plays a keystone ecological role in the peak of the aquatic food chain, such negative effects put not only personal health at risk but also the stability of the ecosystem **(Hao et al., 2019; Yao et al., 2020)**.

**Bioaccumulation of Toxicants and Terrestrial Invertebrates**

Invertebrates are examples of the terrestrial invertebrates-including the earthworm Eisenia fetida and the snail Cornu aspersum which form an important base to the soil ecosystem functioning but this group is still prone to bioconcentration of metals and organic chemicals that are discharged in the soils due to fertilizer use. Study by Gonzalez-Alcaraz et al. (2020) points out that these phenomena are powerful and dose-dependent, with strong correlation between concentration of contaminated soils and residues in the bone of invertebrates which can be represented by Figure 5 of the study. The findings indicate that an increase in the rate of environmental contamination is associated with an increase in the internal accumulation level, and in turn, these are also accompanied by sublethal physiological intoxication (reduced growth and compromised functions of body organs, respectively)**(González-Alcaraz et al., 2020)**.

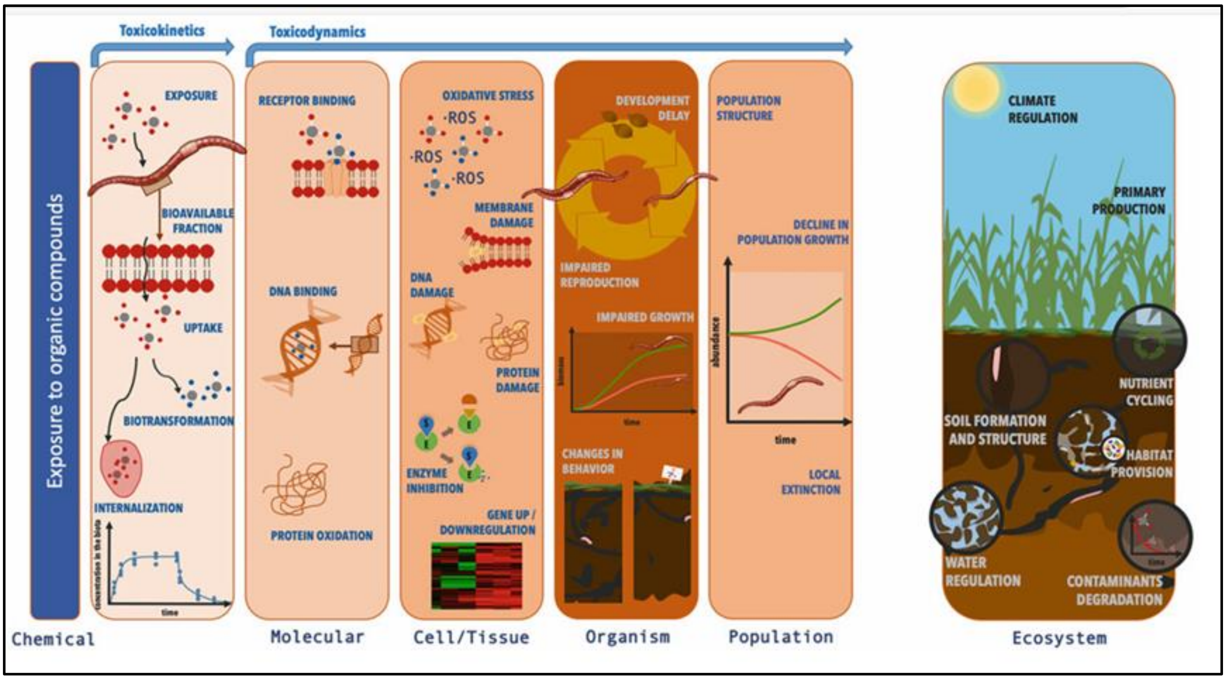


Figure 5: Soil pollution and terrestrial invertebrate chemical accumulation **(González-Alcaraz et al., 2020)**.

The present study reveals that bioaccumulation and toxicity of organic contaminants rely on chemical properties as well as on the species-specific particulars. The study involves very wide array of substances that are commonly found in the environment such as pesticides, pharmaceuticals and industrial products. Chemicals of this nature often occur in mixture in an agronomic environment hence making it difficult to assess the hazard and trophic transfer. The findings indicate that the terrestrial invertebrates play a significant role in the movement of fertilizer-derived toxicants and the implication of such alteration to ecosystem and food-web integrity **(González-Alcaraz et al., 2020; Tison et al., 2024)**.

## Heavy Metal Accumulation in Food Chains

Chronic use of phosphate and nitrogen fertilizers in agriculture often facilitates the accumulation of heavy metals, mostly cadmium (Cd), lead (Pb) and arsenic (As) in soil matrices. This metal accumulation is then transferred to the tissues of the plants, through the processes of biomagnification, the metal concentrations in food webs are increased, which poses significant risks to the integrity of the ecosystems and the health of the population.

## Cadmium/Lead Soil-to-Plant Transaction

Most of the fertilizers produced using phosphate rock possess traces of cadmium (Cd) and lead (Pb), which increase in concentration in the agricultural soil with time. These heavy metals can easily enter the roots of plants and then be conveyed to other parts of the plants even to the parts that are involved in food, like grains. As Khatun et al. (2022) show, overuse and unchecked application of chemical fertilizers contribute to accumulation of Cd and Pb levels in soils hence increasing levels of these components in crops like wheat and rice**(Khatun et al., 2022)**. This build up is a major threat to the safety of food and human health considering that these are toxic metals. The research thus raises the concern that heavy metal concentration should be monitored continuously and that remediation actions should be undertaken to ensure that the heavy metals do not exceed the threshold thereby minimizing environmental contamination and plant absorption**(NIÑO-SAVALA et al., 2019)**.

## Soil-to-Human Cadmium Transfer via Crops

Cadmium (Cd) is a non-essential, hazardous, heavy metal that is mostly exposed to the human food chain through soil-plant-human channel. Jackson and Alloway (2017) have offered a comprehensive survey of all factors which affect the uptake of Cd in crops, indeed, a major influence on Cd uptake in crops is the physicochemical properties of the soil, and in particular acidic pH and phosphate interaction which play critical roles in the relative availability of Cd in the soil to plants. Certain phosphate fertilizers have the capacity to increase Cd concentrations in farming soils and ultimately encourage Cd prevalence in edible food components of crops, including cereals and root tubers, which are the major sources of Cd in human diet. These potential human exposures have been attempted to be modelled through development of predictive models of the Cd transfer coefficients of soil to crops depending on fertiliser history and existing soil circumstances. A detailed understanding of these dynamics is essential to the risk management of the agricultural system Cd and protection of food security all over the world **(Jackson and Alloway, 2017; Wang et al., 2023; Zhang et al., 2025)**.

## Sustainable Alternatives and Mitigation

Over the past few years, increasing ecological cost related with the use of synthetic fertilizing has been pushing contemporary farming towards the resource efficiency and biological-based methods. Modern research justifies a need to integrate organic methods of management such as green manuring, composting, and microbial inoculation into nutrient management practices of the mainstream **(Arora et al., 2024)**. Biofertilizers, and especially those containing phosphate-dissolving bacteria and nitrogen-fixing bacteria are gaining recognition due to their ability to reduce the need of chemical inputs, whilst maintaining crop yields. These microbial formulations enhance soil microbial functions and work synergistically with compost and cover crops and maintain soil fertility and productivity as shown by **(Sharma et al., 2025).** At the same time, the use of the urban and agro-industrial wastes in the framework of the circular economy has become a notable topic of the usage of organic wastes to turn organic food remains to nutrient substrates with prolonged release. Ahmad et al. (2025) emphasize the ability of composting to reduce the amount of fertilizer when increasing the quality of soil by distributing carbon and stimulating microorganisms **(Ahmad et al., 2025)** . Recent empirical data show that legumes-that are widely used in the green manuring activities- are superb in improving the nutrient availability and in altering the rhizosphere processes in the agroecosystems. According to the study of Kumawat et al. (2025), the application of green manures among rice-based production systems coupled with the use of compost and microbial inoculants triggered significant changes in the biological characteristics and yield levels of the various production systems. A combination of these results augers well in ensuring the strategic inclusion of legumes in integrated nutrient management programs, thus fortifying crop productivity and at the same time transforming agricultural systems into resilient ones **(Kumawat et al., 2025).** The development of integrated nutrient management (INM) frameworks (systems that combine the use of reduced chemical fertilizers with organic nutrient sources) are finding increasing support in the current literature as being potentially scalable and more resilient options than individual types of nutrient management. Such systems can increase nitrogen-use efficiency, stabilize yield, and restore soil enzymatic activity, so they are the most important aspects of climate-resilient farming **(Singh et al., 2024)** . Such tactics will therefore serve as green defense and agriculturally beneficial tools in ensuring less use of convention fertilizer and reduced ecological stress of conventionalized fertilizer use **(Babcock-Jackson et al., 2022; Liao et al., 2025; Maaz et al., 2025)**.

## Conclusion

Even though chemical fertilizers increased the overall agricultural output since old times, the huge and prolonged periods of use left significant harm on the ecological level. Extended and prolonged use of fertilizers upsets the microbial communities of soil, promotes leaching of nutrients, pollutes fresh water bodies, induces physiological stress and death of aquatic and terrestrial beings. The heavy metals in fertilizers are built off the food chains, creating a toxic exposure on the wildlife and human beings. In addition, such inputs compromise crop quality and reduce resistance to stressors in the environment. As a counter measure, realistic solutions such as the use of biofertilizers, compost, and the implementation of integrated nutrient strategies in layering through sustainable nutrient management practices offer evidence-based measures that could repair the healthy soils and restore an adequate ecological state besides eliminating environmental pollution and long- term ecological risk. The shift to fertilization with an ecologically balanced mode is the only way to attain sustainable agriculture as well as shielding biodiversity and the wellness of all systems involved in being polluted through chemical fertilizer.

## References


**Adebanjo-Aina, O., and Oludoye, O. (2025).** Impact of Nitrogen Fertiliser Usage in Agriculture on Water Quality. Pollutants **5**, 21.

**Ahmad, A., Javed, M. H., Musharavati, F., Khan, M. I., Al-Muhtaseb, A. a. H., Naqvi, M., Abu, R., Anjum, M. W., Rehan, M., and Asam, Z.-u.-Z. (2025).** Achieving circular economy through sustainable biofertilizer production from mixed municipal waste: a life cycle analysis approach. Biomass Conversion and Biorefinery, 1-19.

**Arora, P. K., Tripathi, S., Omar, R. A., Chauhan, P., Sinhal, V. K., Singh, A., Srivastava, A., Garg, S. K., and Singh, V. P. (2024)**. Next-generation fertilizers: the impact of bionanofertilizers on sustainable agriculture. Microbial Cell Factories **23**, 254.

**Babcock-Jackson, L., Konovalova, T., Krogman, J., Bird, R., and Diaz, L. L. (2022).** Sustainable Fertilizers: Current Publication Landscape and Challenges.

**Bouwman, L., Goldewijk, K. K., Van Der Hoek, K. W., Beusen, A. H., Van Vuuren, D. P., Willems, J., Rufino, M. C., and Stehfest, E. (2013).** Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period. Proceedings of the National Academy of Sciences **110**, 20882-20887.

**Devi, N. T., Devi, A. S., and Singh, K. R. (2025).** Impact of chemical fertilizer and composts application on growth and yield of rice in Northeast India. Scientific Reports **15**, 8575.

**Diao, Y., Li, H., Jiang, S., and Li, X. (2020).** Effects of changing fertilization since the 1980s on nitrogen runoff and leaching in rice–wheat rotation systems, Taihu Lake Basin. Water **12**, 886.

**Erisman, J. W., Sutton, M. A., Galloway, J., Klimont, Z., and Winiwarter, W. (2008).** How a century of ammonia synthesis changed the world. Nature geoscience **1**, 636-639.

**Fujii, K., Zheng, J., Zhou, Z., and Fang, Y. (2024).** Quantitative assessment of soil acidification in four Chinese forests affected by nitrogen deposition. Plant and Soil, 1-15.

**González-Alcaraz, M. N., Malheiro, C., Cardoso, D. N., Prodana, M., Morgado, R. G., van Gestel, C. A., and Loureiro, S. (2020).** Bioaccumulation and toxicity of organic chemicals in terrestrial invertebrates. In "Bioavailability of Organic Chemicals in Soil and Sediment", pp. 149-189. Springer.

**Guan, Q., Tang, J., Feng, L., Olin, S., and Schurgers, G. (2023).** Long-term changes of nitrogen leaching and the contributions of terrestrial nutrient sources to lake eutrophication dynamics on the Yangtze Plain of China. Biogeosciences **20**, 1635-1648.

**Hao, M., Zuo, Q., Zhang, W., Feng, Y., Wang, L., Yu, L., Zhang, X., Li, J., and Huang, Z. (2019).** Toxicological assessment of ammonia exposure on Carassius auratus red var. living in landscape waters. Bulletin of environmental contamination and toxicology **103**, 814-821.

**Hina, N. S. (2024).** Global meta-analysis of nitrate leaching vulnerability in synthetic and organic fertilizers over the past four decades. Water **16**, 457.

**Hossain, M. E., Shahrukh, S., and Hossain, S. A. (2022).** Chemical fertilizers and pesticides: impacts on soil degradation, groundwater, and human health in Bangladesh. In "Environmental degradation: challenges and strategies for mitigation", pp. 63-92. Springer.

**Hou, Y., Zeng, W., Hou, M., Wang, Z., Luo, Y., Lei, G., Zhou, B., and Huang, J. (2021).** Responses of the soil microbial community to salinity stress in maize fields. Biology **10**, 1114.

**Huang, J., Xu, C.-c., Ridoutt, B. G., Wang, X.-c., and Ren, P.-a. (2017).** Nitrogen and phosphorus losses and eutrophication potential associated with fertilizer application to cropland in China. Journal of Cleaner Production **159**, 171-179.

**Iqbal, A., He, L., Ali, I., Yuan, P., Khan, A., Hua, Z., Wei, S., and Jiang, L. (2022).** Partial substation of organic fertilizer with chemical fertilizer improves soil biochemical attributes, rice yields, and restores bacterial community diversity in a paddy field. Frontiers in plant science **13**, 895230.

**Jackson, A. P., and Alloway, B. J. (2017).** The transfer of cadmium from agricultural soils to the human food chain. Biogeochemistry of trace metals, 121-170.

J**ianHua, J., ZhenZhen, L., ShuZhen, L., HongQian, H., YiRen, L., XiuMei, L., XuHua, L., and XianJin, L. (2024).** Long-Term Application of Chemical Fertilizers Induces Soil Acidification and Soil Exchangeable Base Cation Loss on Paddy in Southern China. Scientia Agricultura Sinica **57**, 2599-2611.

**Jote, C. A. (2023).** The impacts of using inorganic chemical fertilizers on the environment and human health. Organic and Medicinal Chemistry International Journal **13**, 555864.

**Khatun, J., Intekhab, A., and Dhak, D. (2022).** Effect of uncontrolled fertilization and heavy metal toxicity associated with arsenic (As), lead (Pb) and cadmium (Cd), and possible remediation. Toxicology **477**, 153274.

**Kumawat, A., Kumar, D., Shivay, Y., Sangwan, S., Yadav, D., Pooniya, V., Ali, S., Madhu, M., Rashmi, I., and Bhargavi, B. (2025).** Exploring Optimal Combinations of Green Manures, Composts, and Microbial Inoculums to Boost Soil Biological Properties, Nutrient Release, and Basmati Rice Yield. International Journal of Plant Production **19**, 99-116.

**Liao, F., Zheng, Y., and Wang, X. (2025).** Promoting the replacement of chemical fertilizer with organic fertilizer: the role of policy incentives and digital technology. Frontiers in Sustainable Food Systems **9**, 1527913.

**Maaz, T. M., Dobermann, A., Lyons, S. E., and Thomson, A. M. (2025).** Review of research and innovation on novel fertilizers for crop nutrition. npj Sustainable Agriculture **3**, 25.

**NIÑO-SAVALA, A. G., ZHUANG, Z., MA, X., FANGMEIER, A., LI, H., TANG, A., and LIU, X. (2019).** Cadmium pollution from phosphate fertilizers in arable soils and crops: An overview. Frontiers of Agricultural Science and Engineering **6**, 419-430.

**Niu, H., Pang, Z., Fallah, N., Zhou, Y., Zhang, C., Hu, C., Lin, W., and Yuan, Z. (2021).** Diversity of microbial communities and soil nutrients in sugarcane rhizosphere soil under water soluble fertilizer. Plos one **16**, e0245626.

**Pahalvi, H. N., Rafiya, L., Rashid, S., Nisar, B., and Kamili, A. N. (2021).** Chemical fertilizers and their impact on soil health. In "Microbiota and biofertilizers, Vol 2: Ecofriendly tools for reclamation of degraded soil environs", pp. 1-20. Springer.

**Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., and Schellnhuber, H. J. (2009).** A safe operating space for humanity. nature **461**, 472-475.

**Salem, M. A., Bedade, D. K., Al-Ethawi, L., and Al-Waleed, S. M. (2020).** Assessment of physiochemical properties and concentration of heavy metals in agricultural soils fertilized with chemical fertilizers. Heliyon **6**.

**Sharma, N., Dixit, B., and Kayastha, R. (2025).** Proactive approach to biofertilizers for sustainable agriculture. Journal of Plant Nutrition, 1-19.

**Singh, S., Devi, N. B., Divya, D., Kumar, A., Singh, S., Tyagi, G., and Kumar, A. (2024).** Soil fertility management: Role of organic amendments and bio-fertilizers: A review. International Journal of Research in Agronomy **7**, 766-772.

**Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., De Vries, W., and De Wit, C. A. (2015).** Planetary boundaries: Guiding human development on a changing planet. science **347**, 1259855.

**Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., and Polasky, S. (2002).** Agricultural sustainability and intensive production practices. Nature **418**, 671-677.

**Tison, L., Beaumelle, L., Monceau, K., and Thiéry, D. (2024).** Transfer and bioaccumulation of pesticides in terrestrial arthropods and food webs: State of knowledge and perspectives for research. Chemosphere **357**, 142036.

**Wang, B., Wang, P., Zhao, S., Shi, H., Zhu, Y., Teng, Y., Jiang, G., and Liu, S. (2023).** Combined effects of microplastics and cadmium on the soil-plant system: phytotoxicity, Cd accumulation and microbial activity. Environmental Pollution **333**, 121960.

**Wang, X., Sanderman, J., and Yoo, K. (2018).** Climate-dependent topographic effects on pyrogenic soil carbon in southeastern Australia. Geoderma **322**, 121-130.

**Xu, Z., Cao, J., Qin, X., Qiu, W., Mei, J., and Xie, J. (2021).** Toxic effects on bioaccumulation, hematological parameters, oxidative stress, immune responses and tissue structure in fish exposed to ammonia nitrogen: a review. Animals **11**, 3304.

**Yao, Z., Zhang, X., Lai, Q., Zhou, K., and Gao, P. (2020).** Acute exposure to key aquaculture environmental stressors impaired the aerobic metabolism of Carassius auratus gibelio. Biology **9**, 27.

**Zhang, R., Zhu, Y., Li, H., and Sun, N. (2025).** Recent advances in understanding the mechanisms of plant cadmium accumulation as affected by grafting in vegetable production. Frontiers in Plant Science **16**, 1526041.

**Zhang, X., Davidson, E. A., Mauzerall, D. L., Searchinger, T. D., Dumas, P., and Shen, Y. (2015).** Managing nitrogen for sustainable development. Nature **528**, 51-59.