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Urea Fertilizer: A Journey from an Essential Nutrients to an Emerging Pollutant

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Abstract
Urea, a cornerstone of modern agriculture, is widely recognized for its high nitrogen content and cost-effectiveness. Since the mid-20th century, it has played a critical role in enhancing crop yields and ensuring global food security. However, its excessive application has resulted in severe environmental consequences, including soil acidification, water eutrophication, and greenhouse gas emissions. This review presents a balanced perspective of urea that aims to optimize agricultural productivity while mitigating ecological harm. It also examines chemical properties, historical significance, and global usage trends alongside the environmental and health impacts of urea.
Additionally, this review article explores sustainable agricultural practices such as crop rotation, composting, and organic farming, as well as alternative nitrogen-based fertilizers derived from pharmaceuticals and biofuels. This literature survey is based on a comprehensive review of scientific literature, cross-referenced data from reliable sources, and an evaluation of global policies. By integrating scientific insights with policy discussions, this review presents a balanced perspective that aims to optimize agricultural productivity while mitigating environmental harm.
Keywords: Urea, crop, soil acidification, biofuel, agricultural productivity, environmental protection

1. INTRODUCTION

Urea, a vital nitrogen-based compound, has been a key component of agricultural practices globally since the 1950s. It accounts for over half of the world's nitrogen fertilizer usage due to its affordability and effectiveness in boosting crop yields. In South Asian countries, urea is the oldest fertilizer, and it is widely used in rice and wheat crops as an affordable method to boost crop yields and improve soil fertility. Given the high demands of food production in densely populated areas of the world, urea has become the most commonly applied fertilizer. However, while urea plays a crucial role in enhancing crop productivity, its excessive use has led to serious environmental concerns, including soil degradation, water pollution, and greenhouse gas emissions [1]. This review article explores the dual nature of urea and its journey from an essential nutrient to an emerging pollutant. It explores its chemical composition, historical development, and global consumption trends while also addressing the adverse effects of overuse.
Furthermore, we search for policies aimed at regulating urea pollution and discuss sustainable farming practices such as crop rotation, composting, and organic farming as potential solutions. By exploring the environmental consequences, including soil depletion, water pollution, and harm to biodiversity, we will underscore the increasing recognition of urea as an ecological threat. Urea, once celebrated as a vital fertilizer, is now emerging as a significant environmental pollutant due to its overuse. The excessive application of urea has led to severe consequences, including soil degradation, water contamination, and increased greenhouse gas emissions.
Furthermore, the article will discuss government evaluations, government recognition of urea as a pollutant, and the role of sustainable agriculture practices in mitigating its adverse effects. Given the urgent need for eco-friendly alternatives, this study also explores spent microbial biomass (SMB) as a sustainable nitrogen source [2].

2. CHEMICAL MAKEUP AND PHYSICAL PROPERTIES OF UREA

Urea is, in many ways, the most convenient form of fixed nitrogen (N). It has the highest N content available in a solid fertilizer (46%). It is easy to produce as prills or granules and easily transported in bulk or bags with no explosive hazard. It leaves no salt residue after use on crops. Its specific gravity is 1.335; it decomposes on boiling and is reasonably soluble in water. [3]. Urea is a nitrogen-containing organic compound containing 46% N and is crucial in the N cycle. It is widely used in fertilizers. It is also called carbamide and diamide of carbonic acid because of the presence of the carbonyl group and two amine groups. The chemical composition of Urea primarily consists of the compound urea itself, which is represented by the chemical formula $CO(NH_2)_2$. The molecular structure includes two amine groups (NH_2) and one carbonyl group(C=O), contributing to its high nitrogen content (Fig.1). urea can be found in various formulations, often combined with other components to enhance its properties and applications. The carbon atom is bonded to the oxygen atom via a double bond and to two nitrogen atoms via single bonds, contributing to its stability and solubility in water [4].

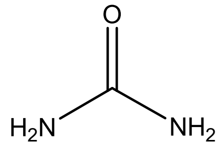

Figure 1: Chemical structure of urea.

The invention discloses urea-based compound fertilizer containing high-activity minerals. The urea-based compound fertilizer comprises raw materials in percentage by weight as follows: 20%-30% of urea, 30%-40% of ammonium chloride, 10%-20% of mono ammonium phosphate, 10%-20% of potassium chloride, 1%-1.5% of sulfuric acid and 2%-3% of liquid ammonia. The urea-based compound fertilizer containing high-activity minerals can promote root growth and nutrition absorption of crops and regulate a soil structure [5].

2.1. Historical background of urea

Urea (chemical formula: CH_4N_2O), also known as carbamide, is a polar, hygroscopic molecule produced by the human body that was first discovered in urine in 1773 by the French chemist Hilaire Rouelle. In 1828, the German chemist Friedrich Wöhler obtained urea by treating silver cyanate with ammonium chloride in a failed attempt to prepare ammonium cyanate. In the second part of the 20th century, the importance of urea in the treatment of wound healing declined as it was overcome by the development of more specific and compelling medications, while its use as moisturizers and keratolytic agents became more popular. The year 1957 represents an essential date for urea, as Kligman first reviewed its dermatological uses, focusing his attention in particular on its bacteriostatic and proteolytic properties. He reported that, although in vitro, 10% urea-containing solutions may exhibit an antibacterial effect on a variety of microorganisms, in vivo, higher concentrations (exceeding 40%) are necessary to be effective in dermatologic disorders [6]. Urea has been the primary nitrogenous fertilizer globally since the early 1950s, and it is recognized for its high N content of approximately 46%. Approximately 220 million tons are produced annually to meet agricultural demands despite significant nitrogen loss during soil application [7].

Synthetic urea was first utilized as a fertilizer around World War I, with its manufacture beginning in Germany. By 1921, urea was being tested in agricultural experiments, including those conducted in the UK at Rothamsted. Sir John Russell noted in 1939 that in experiments at Rothamsted and Woburn, Urea showed performance roughly equivalent to that of ammonium sulfate. Over the years, the development of urea as a fertilizer involved multiple experimental phases conducted by Imperial Chemical Industries Ltd. These included trials in 1928-34, 1951-52, and a more extensive series starting in 1956. Early trials demonstrated that urea performed comparably to other nitrogenous fertilizers across a variety of crops. The later experiments focused on high-rate applications on grassland and cereals to evaluate their effectiveness, particularly for "early bite" grazing [8]. Urea has evolved as a fertilizer since its introduction in 1935. By the 1960s, urea had become more widely adopted due to improved efficiency and management practices. Urea now constitutes a significant portion of global nitrogen fertilizer usage, particularly in rice cultivation, where it accounts for 80% of nitrogen fertilizer used. [9].

2.2. Transition of Urea from an essential fertilizer to an emerging pollutant

Urea became the cornerstone of modern agriculture due to its high nitrogen content, water solubility, and adaptability across various crops. Its economic appeal stems from the affordability and availability of raw materials, such as carbon dioxide (CO_2) and ammonia (NH_3). These factors have made urea an indispensable component of global agriculture, with consumption levels significantly surpassing those of alternative fertilizers like ammonium nitrate. Urea's comparative advantages include its higher yield efficiency, lower corrosiveness, and ability to act as a carrier for herbicides [8,10]. However, this widespread use has exposed its potential environmental and agricultural challenges. Although urea is rarely used in hydroponic cultures, it remains a significant nitrogen source in conventional agriculture. Its hydrolysis to ammonium in soil can lead to a drastic pH decrease, toxicity, and nutrient uptake interference, limiting its use in hydroponics. Nutritionally, urea also plays an intriguing role in human physiology by recycling nitrogen during protein digestion, particularly benefiting infants and individuals recovering from illness. Despite these benefits, the industrial-scale use of urea has unveiled pressing environmental concerns. The industrial production of urea generates substantial waste, particularly during concentration processes in evaporators. Water vapour containing urea droplets escapes into the condensate, and auxiliary operations like cleaning towers and centrifuging crystals further contribute to wastewater generation. Agricultural runoff and industrial effluents compound the issue, introducing significant amounts of urea into ecosystems. Urea's impact on greenhouse gas emissions is particularly alarming. As it decomposes in the soil, urea releases nitrous oxide (N_2O), a potent greenhouse gas with a global warming potential far exceeding that of CO_2[11].

Moreover, urea volatilization leads to the loss of ammonia (NH_3), further polluting the environment and diminishing its efficiency as a fertilizer. These processes underscore urea's role in both the greenhouse effect and ozone layer depletion. The challenges extend to its application in agriculture[12]. Urea's toxicity can render it ineffective, as demonstrated in studies with maize grown in varying soil types. In neutral sandy loam, delayed ammonification and nitrification processes lead to toxic accumulations of ammonia and nitrile. High pH levels exacerbate this toxicity, necessitating pH adjustments with phosphoric or sulfuric acid. Conversely, in acidic soils, the persistence of urea and ammonium accumulation causes similar toxic effects. These dynamics highlight the delicate balance required to utilize urea effectively. As the global reliance on urea persists, its dual role as a crucial agricultural input and a contributor to environmental degradation becomes increasingly apparent. Mitigation strategies, such as adopting slow-release fertilizers and nitrification inhibitors, can help reduce their adverse effects. However, the challenges associated with urea underscore the urgent need for sustainable agricultural practices to address its significant environmental impact [13,14].

2.3. Current global patterns of urea usage

India is the largest consumer of synthetically produced fertilizers, with a significant increase in N fertilizer consumption over the decades, particularly urea, which is widely used in wheat and rice systems across South Asia due to its high N content and bioavailability. Urea is commercially available as prills, granules, or super granules, while liquid forms like urea ammonium nitrate (UAN) are also popular. UAN contains nitrogen in three forms: nitrate (25%), immediately available to plants; ammonium (25%), readily assimilated or converted to nitrate; and urea-derived nitrogen (50%), hydrolyzed to ammonium and then converted to nitrate. UAN enhances nutrient uptake when applied appropriately, using methods like soil injection, foliar application, or fertigation, with optimal application depths minimizing seed toxicity and optimizing nutrient availability [15]. In wheat systems, nitrogen application rates range from 60 to 150 kg/ha depending on soil conditions, with additional nitrogen needed in alkali soils to address salinity and sodicity challenges, and efficiency is often improved by splitting applications across planting, early, and late growth stages. Urea is also a key component in producing complex fertilizers like NPK and has industrial applications in plastics, adhesives, and cosmetics [16,17].

3. ENVIRONMENTAL HAZARDS OF UREA

3.1 Effect of Urea on Air

Urea, once celebrated as a groundbreaking agricultural innovation due to its nitrogen-rich composition, has now emerged as a growing environmental concern. Widely used in farming to enhance crop yields, urea undergoes chemical transformations that have far-reaching impacts on ecosystems. The application of urea fertilizers significantly impacts air quality through the emission of various toxic gases like nitrogenous gases, particularly ammonia (NH_3) and nitrous oxide (N_2O) [17]. These emissions contribute to air pollution and have implications for human health and environmental quality. Urea fertilizers can lead to NH_3 emissions. Reductions in ammonia emissions are to be included in the forthcoming "multipollutant multi-effects" protocol agreed on by the United Nations Economic Commission for Europe (UNECE) Convention on Long-Range Transboundary Air Pollution. Agriculture is responsible for about 80–90% of NH_3 emissions, of which about 10–20% is from N fertilizers. While NH_3 emissions from N fertilizers such as ammonium nitrate (AN) are considered to be small (∼1–3%), those from urea are estimated to be much greater at ∼10–20% of total N application and have been estimated to contribute 50% of NH_3 emissions from fertilizers in western Europe Figure (2) express the depicts the phenomenon [14, 18].

Figure 2: Leaf burn due to NH_3 produced through hydrolysis of urea.

Ammonia (NH_3) is one of the most common nitrogen gas species and pollutants present in the lower troposphere. Ammonia enters the atmosphere through volatilization from soils through the usage of nitrogen-based fertilizers in agriculture. Because of its short lifetime (up to a few hours), ammonia is highly reactive. It can react chemically with acids in the atmosphere to form fine particulate matter (PM2.5), playing an important role in secondary aerosol formation. The wet and dry deposition of ammonia on soils and water bodies has been shown to be detrimental to ecosystem biodiversity as it leads to the acidification of the environment, which in turn can lead to changes in species composition and other deleterious effects. Therefore, observations of ammonia are essential for establishing air quality and environmental regulations for agricultural practices.

The application of urea in agricultural soil significantly boosts nitrous oxide (N_2O) emissions. Short-term Nitrogen-Oxidizing Bacteria suppression during urea hydrolysis played a crucial role in increasing N_2O emissions from agricultural soils. Like other greenhouse gases, nitrous oxide absorbs radiation and traps heat in the atmosphere, which can persist for an average of 114 years. According to the EPA, it is placed in the middle ground among super-pollutants. Compared with carbon dioxide, which can live in the atmosphere for hundreds of years, nitrous oxide is around a relatively short time. However, it lasts significantly longer than other short-lived climate pollutants like black carbon or methane. Nitrous oxide is also about 300 times more potent than carbon dioxide in terms of its warming effect, and it also contributes to the depletion of the ozone layer. In the stratosphere, nitrous oxide is exposed to sunlight and oxygen, which converts the gas into nitrogen oxides. The nitrogen oxides can damage the ozone layer, which humans rely on to prevent most of the sun's ultraviolet radiation from reaching Earth's surface [19-20].

4. EFFECT ON LIVING THINGS

4.1 Plants

The impact of urea fertilizer on living organisms is complex, influencing both plant growth and human health in diverse ways. As a primary nitrogen source, urea is very significant for crops, enhancing growth and photosynthetic activity. The sections that follow delve deeper into these varied effects. Although urea usually has low eco-toxicity to organisms, indirect and long-term deleterious effects on the ecosystems, such as eutrophication, groundwater pollution, and soil acidification, the product of urea hydrolysis (ammonium) is more toxic to plants. It significantly influences the water quality and deteriorates the oxygen regime in water bodies [21].

Excessive urea exposure stunts root growth, reduces the number of roots, and slows down cell division in root tissues. This can be seen from an experiment that uses onion bulbs. Onion bulbs were placed in water for 2 days to start growing roots. After this, they were moved into solutions with different urea levels: 0%(just water), 0.005%, 0.01%, 0.025%, and 0.05% urea. Each onion sat in its solution for 1 day. The scientists looked at both visible changes like root length and root number and microscopic changes like cell division in the onion roots. As the amount of urea increased, both the root length and the number of roots decreased. This means the higher the urea concentration, the less the roots grew. Urea also slows down cell division in the roots. In healthy roots, cells divide actively to help the roots grow. Still, as urea concentration went up, fewer cells were dividing, causing a drop in the mitotic index, which is a measure of how many cells are actively dividing, and an increase in mitotic inhibition, which is a measure of how much cell division is being blocked [22].

It is well known that high doses of urea cause physiological disorders leading to reduced biological productivity of plants. Urea, at low concentrations in the medium (100 mg L^{-1}), induced oxidative stress in *Elodea* leaves due to the formation of proline and soluble protein and total nitrogen in *E.* dense leaves spiked with different concentrations of urea. The adverse effects of urea fertilizers on seed germination and seedling growth in soil are due to NH_3 produced through hydrolysis of urea by soil urease. The addition of a urease inhibitor to these fertilizers can eliminate them. It has also shown that leaf burns commonly observed after foliar fertilization of soybeans with urea result from the accumulation of toxic amounts of urea in soybean leaves rather than the formation of toxic amounts of NH3 through the hydrolysis of urea by leaf urease. It further showed that this leaf burn is accordingly increased rather than decreased by the addition of a urease inhibitor to the urea fertilizer applied (Fig. 2). It completely damaged the leaf (Fig.2) [23].

4.2. Animals

The adverse effects of urea fertilizer on human health are complex, mainly due to its chemical nature and environmental impact. Overuse of Urea can cause nitrates to build up in food and water, which has been connected to severe health problems, including thyroid disorders, certain cancers, and developmental defects in fetuses. Additionally, urea exposure in occupational settings has been associated with respiratory issues, including obstructive lung changes and bronchospasm, particularly in fertilizer plant workers[24]. Nitrogen fertilizers are directly absorbed by plants or transformed into various other forms by the oxidation process. Still, when the nitrate is not absorbed, it flows into the soil together with water, where the excess nitrogen increases the risk of environmental pollution. Human consumption of water or crops contaminated with high nitrate concentration is leading to health injuries. Through excessive application of fertilizers with nitrogen, high concentrations of nitrates can accumulate in the edible parts of plants. Generally, green leafy vegetables contain the highest levels of nitrates and pose several health risks to animals. The statistical analysis of the obtained results indicates that mitotic activity is inhibited with the increase in urea concentration.

In contrast, the chromosomal aberration rate in the cells in mitosis, as well as the frequency of nuclear abnormalities in the interphase cells, increases. From this point of view, the primary chromosomal aberrations identified were stickiness, laggards, and C-mitosis. At the same time, nuclear abnormalities were the appearance of a large number of binuclear and multinucleated cells, some with ghost nuclei. In addition, at concentrations of over 1000 ppm and especially at 10,000 and 20,000 ppm urea, the presence of cells with one or more micronuclei (even with nine micronuclei) was signaled, indicating a strong clastogenic potential of urea [25].

Urea also increases oxidative stress by creating an imbalance between harmful reactive oxygen species and the body's antioxidant defenses, which can damage cells and tissues. It also led to a decrease in insulin production, likely impairing glucose metabolism and possibly increasing the risk of conditions like insulin resistance and metabolic disorders. Furthermore, urea compromised glycolysis, leading to impaired beta cell glycolysis, in which glucose is broken down for energy in pancreatic beta cells, which may interfere with insulin secretion and energy regulation in these cells. Urea also causes endothelial dysfunction, in which endothelial cells lining blood vessels are affected, potentially impairing blood flow and increasing the risk of cardiovascular complications. Loss of synaptic function, which is the function of the endothelial system, is also the cause of urea, in which urea exposure leads to a reduction in synaptic connections between neurons, which can impair communication with the nervous system and affect cognitive functions. Urea exposure also

impaired the sense of smell, possibly due to its impact on the nervous system, particularly the areas associated with olfaction, ultimately leading to a decrease in olfactory function [26].
An experiment was done to evaluate how toxic urea fertilizer is to young Nile tilapia fish (*Oreochromis niloticus*) (Fig.3) The results showed that as the concentration of urea increased, more fish died, with a lethal concentration (LC50) set at 500 mg/l. Higher urea levels also raised the total dissolved solids in the water. Key water quality factors, including temperature, electrical conductivity, dissolved oxygen, and pH, changed significantly ($P < 0.05$) as urea levels rose. During the test, the fish showed clear signs of distress, such as increased excitement, fast swimming, and loss of balance, which ultimately led to death. This study clearly shows that high levels of urea fertilizer are highly toxic to young Nile tilapia[27].

Figure 3: Effect of Urea on *Nile Tilapia*, (*Oreochromis niloticus*).

4.3. Effect on Soil
The soil quality showed a toxic effect on soil quality. The conversion of ammonium to nitrate (nitrification) produces hydrogen ions, which, after leaching into the soil, cause a lowering of soil pH over time (Fig.4). Acidic soils inhibit microbial activity and reduce nutrient availability, harming long-term soil health. The Environmental Protection Agency (EPA) has set the maximum contaminant level as 10 mg/l of nitrate as nitrogen in the United States, whereas in India, the acceptable limit by the Bureau of Indian Standards (BIS) is 45 mg/l as nitrate. A study in China, where intensive farming and high rates of nitrogen fertilizer were applied for 20 years, showed that soil pH dropped by 0.30–0.80 units from the original level. Leaching removes valuable nutrients like nitrogen from the soil, reducing soil fertility. This decreases the availability of essential elements for plant growth, potentially leading to lower crop yields. It was estimated that leaching from agricultural soil could account for up to 35–58% of total soil nitrogen losses. In poorly managed systems, repeated and excessive urea use can lead to salt accumulation in the soil. This salinity stress can reduce crop yields and impair soil structure. Excessive urea use in poorly managed systems leads to salt buildup, raising soil salinity (above 4 dS/m) and causing osmotic stress that limits water uptake by crops. Salinity affects 20% of irrigated lands worldwide, with crop yields like wheat dropping 13% per 1 dS/m increase. High sodium levels (>15% ESP) further degrade soil structure. Proper urea management and salt leaching can mitigate these effects [28].

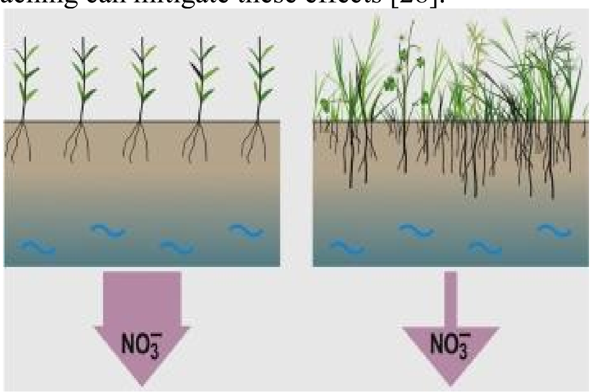

Figure 4: Leaching of Nitrate into soil.

4.4 Effect on Water
Runoff containing urea or its nitrogenous byproducts can enter surface water bodies, causing eutrophication. This process stimulates excessive algae growth, which depletes oxygen levels, harms aquatic life, and disrupts ecosystems. When urea volatilizes, it releases ammonia gas into the air. This ammonia can settle back into water systems, leading to increased nitrogen pollution and contributing to water acidification. A major environmental issue linked to urea use is nitrate leaching into groundwater. When ammonium from urea is converted to nitrate, the nitrate ions, which are highly soluble and mobile, move quickly through the soil. This process can lead to contamination of aquifers, posing serious risks to drinking water quality and human health. Elevated nitrate levels in drinking water are linked to health problems, including "blue baby syndrome" in infants and potential long-term effects on adults. In moderate amounts, nitrate is a harmless constituent of food and water; hence, a permissible limit of 50 mg/l as nitrate ion in drinking water is specified

by the World Health Organization (WHO) to protect against methemoglobinemia. The amount of leaching increased with increasing rainfall intensity, accounting for 25.82%, 47.60%, and 64.74% of the total water transfer under rainstorm, heavy rainstorm, and extreme rainstorm scenarios, respectively. Nitrate leaching is more significant in sandy than clayey soils due to the presence of a large number of macro pores, and leaching is higher in humid than arid and semiarid regions due to differences in annual precipitation. Nitrate-N leaching occurs mainly in the fall, winter, and spring seasons in the northern hemisphere when evapotranspiration is low, crops are absent to uptake soil nitrogen, and precipitation exceeds the water-holding capacity of the soil[28]

5. GLOBAL RECOGNITION OF UREA AS A POLLUTANT AND GOVERNMENT POLICIES REGARDING THIS MATTER

Urea is globally acknowledged as vital for ensuring food security while also contributing to environmental issues, leading to the implementation of policies aimed at reducing its harmful effects without compromising agricultural output. The Kyoto Protocol has recognized nitrous oxide (N_2O), a byproduct resulting from urea usage, as a significant greenhouse gas, thereby indirectly targeting its agricultural origins. Fertilizer industries worldwide have embraced climate action plans focused on lowering emissions through the development of slow-release fertilizers, enhancements in production techniques, and the promotion of precision application methods. The international community's awareness of urea's dual significance has also spurred the development of nitrogen emission models and optimization strategies designed to improve its efficiency while lessening environmental impact. These initiatives demonstrate a dedication to reconciling the essential role of urea in meeting food needs with the pursuit of climate objectives and the protection of ecosystems [29].

6. SUSTAINABLE AGRICULTURAL PRACTICES

6.1. Crop Rotation:

Crop rotation is a very convenient and sustainable method. It can optimize resource use and reduce pest and disease cycles. It can improve the fertility of the soil and diversify the income streams. The technique is highly viable to small-scale farmers as it reduces the reliability of the crop field on expensive chemicals, pesticides, and fertilizers. It promotes sustainability, improves soil health, supports food security, and is a great initiative in building resilience against climate variability. A study was conducted by Hassaan et al [30], and it centered mainly on small-scale farmers of Punjab, Pakistan. In Sargodha and Chakwal, significant benefits of crop rotation were observed in boosting yields and reducing input costs.

Table 1: Differences in yields and seed costs in Rotational and Non-Rotational fields of Sargodha and Chakwal

Location	Rotational Yield (kg/ha)	Non-Rotational Yield (kg/ha)	Seed Cost (per ha)	Profitability Increase (per ha)
Sargodha	2882	2297	$132 vs $145	$1717
Chakwal	2988	3344	$143 vs $105	$2123

In farms practicing crop rotation, better yields were reported with averages of 2882 kg/ha in Sargodha and 2988 kg/ha in Chakwal, which were compared to non-rotational yields of 2297 kg/ha and 3344 kg/ha respectively. The reduced seed costs were also observed due to pest cycle disruption and enhanced soil health with a cost-saving difference in Sargodha ($132 vs $145 per ha) and Chakwal ($143 vs 105$ per ha). This led to a remarkable increase in profitability (1717 per ha and 2123, respectively) [30]. Differences in yields and seed costs in Rotational and Non-Rotational fields is clearly visible in Table (1).

6.2. Composting

Composting is an environmentally benign process that, through microbial activity, converts organic materials like food scraps, plant debris, and biodegradable garbage into nutrient-rich humus. This humus, often referred to as compost, contains roughly 2% nitrogen, 0.5–1.0% phosphorus, 2% potassium, and trim levels of micronutrients, making it an excellent soil amendment. The composting process improves the physical structure of the soil, boosts its fertility, and enriches it with beneficial bacteria. Additionally, composting increases the soil's ability to retain water, thereby lowering the frequency and volume of crop irrigation required. In regions where soil often lacks organic matter and micronutrients, such as in India, composting can help restore these essential elements and support increased agricultural productivity. The importance of composting can also be emphasized in the management of invasive weeds, such as *Trianthema portulacastrum*, *Solanum nigrum*, *Calotropis procera*, and *Parthenium hysterophorus*. These weeds, which frequently pose problems in agricultural settings, were broken down in composting pits, producing compost with high levels of calcium, nitrogen, phosphorus, and potassium and low carbon-to-nitrogen ratios. This approach not only facilitates the recycling of organic materials but also reduces the need for chemical inputs[31].

6.3. Organic farming

Natural farming, also known as chemical-free or do-nothing farming, is an approach to agriculture that harmonizes with nature by avoiding synthetic chemicals, genetically modified seeds, and heavy machinery. Instead, it relies on low-cost, locally sourced inputs and techniques such as cow dung and urine concoctions, mulching, and companion cropping, which support soil fertility and minimize irrigation needs. This approach aims to reduce production costs, support rural employment, and address issues such as food insecurity, farmer distress, and the health impacts of chemical residues in food and water. The ultimate goals of natural farming are to create resilient ecosystems, improve crop yields, restore soil health, preserve biodiversity, and reduce climate-related vulnerabilities. By adopting this approach, farmers can enhance their livelihoods while contributing to a more sustainable and environmentally conscious food system[32].

6.4. A sustainable alternative for nitrogen-containing fertilizers

Chemicals, textiles, pharmaceuticals, and biofuels. This biomass, which is often discarded in landfills or incinerated, contains high levels of nitrogen (~11% dry matter) and essential plant nutrients like calcium, potassium, and phosphorus, making it a viable crop as urea-based fertilizers increasingly contribute to environmental degradation through nitrogen runoff and greenhouse gas emissions, alternative nitrogen sources such as spent microbial biomass (SMB) are being explored for sustainable agricultural practices. SMB is a nutrient-rich organic co-product of white biotechnology processes, where bacterial, fungal, or plant cells act as biocatalysts to synthesize bio-based nitrogen sources. Research has demonstrated that SMB when applied to crops like corn and tall fescue, releases nitrogen over time through mineralization, similar to manure-based amendments. In controlled field studies, SMB application yielded plant biomass and crop nitrogen status comparable to those of conventional synthetic fertilizers. Additionally, long-term benefits include reduced reliance on synthetic fertilizers, lower environmental impact, and improved waste management by repurposing industrial byproducts into valuable agricultural inputs [33,34], which need to re-evaluate current farming practices and adopt more sustainable approaches to mitigate these adverse effects.

6.5. Recommendations

To address these challenges, transitioning to eco-friendly agricultural practices is imperative. Strategies such as crop rotation, composting, and organic farming not only help restore soil health but also reduce reliance on synthetic fertilizers. Additionally, technological innovations like slow-release fertilizers and bio-based nitrogen alternatives present promising solutions. These advancements can help maintain agricultural productivity while minimizing environmental harm, offering a balanced approach to sustainable farming.

Embracing these strategies is not just a choice but a necessity for ensuring the long-term sustainability of agriculture and ecological stability. By integrating these practices, one can mitigate the environmental impact of urea overuse, protect natural resources, and secure food production for future generations. This shift requires a collective effort from farmers, policymakers, and researchers to promote and implement sustainable agricultural practices on a global scale.

CONCLUSION

The transformation of urea from a vital agricultural input to an environmental concern emphasizes the complexity of modern farming practices. While its benefits in enhancing crop productivity are undeniable, the ecological costs of its overuse cannot be overlooked. Urea contributes to air and water pollution, soil degradation, and health risks through mechanisms such as nitrous oxide emissions and nitrate leaching. Addressing these challenges requires a multifaceted approach. Sustainable agricultural practices like crop rotation, composting, and organic farming offer practical solutions to mitigate the adverse effects of urea. Moreover, global policy frameworks and innovations in fertilizer technologies, such as slow-release formulations, are critical in reducing its ecological footprint. Going ahead, a collective effort involving policymakers, researchers, and farmers is essential to ensure that urea's benefits are optimized while minimizing its environmental impact. This balanced approach is pivotal for achieving long-term agricultural sustainability and environmental protection.

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