

Comparative Evaluation of Organic and Inorganic Fertilizers on Maize Productivity

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Abstract

Maize (*Zea mays* L.), a cornerstone of global food security and Pakistan's third-largest cereal crop, exhibits high genetic yield potential yet remains heavily dependent on nutrient inputs, with intensive inorganic fertilizer use driving productivity gains alongside soil degradation, groundwater nitrate contamination, and greenhouse gas emissions. This review synthesizes comparative field and controlled studies evaluating organic fertilizers (farmyard manure, compost, poultry manure, vermicompost, green manures) versus inorganic sources (urea, DAP, NP formulations) and integrated nutrient management (INM) strategies in maize systems. Results consistently show that sole inorganic fertilization maximizes short-term grain yield (8–12 t ha⁻¹) but leads to declining soil organic carbon (SOC), reduced microbial activity, and elevated N₂O emissions. Organic amendments alone sustain or slightly reduce yield (6–9 t ha⁻¹) while significantly improving soil health indicators SOC (+0.2–0.8%), aggregate stability, microbial biomass carbon, enzyme activities (dehydrogenase, urease), and water-holding capacity and lowering nitrate leaching risk. Integrated approaches (e.g., 50–75% inorganic N replaced by organic sources) achieve near-parity with full inorganic yields (8–11 t ha⁻¹), enhance nutrient use efficiency (N recovery up 15–35%), reduce fertilizer costs (10–25%), and deliver superior long-term soil quality and environmental outcomes (lower GWP, improved C sequestration). Climate-resilient benefits include better drought tolerance and nutrient cycling under rainfed or deficit irrigation conditions prevalent in Pakistan. Adoption barriers lower initial nutrient release from organics, labor for composting, and farmer risk aversion are addressed through policy incentives, extension on INM packages, and localized research on optimized organic–inorganic ratios. The evidence supports a paradigm shift toward integrated, organic-enriched fertilization as a sustainable pathway for maintaining maize productivity while reversing soil degradation and mitigating environmental externalities in resource-constrained agroecosystems.

Keywords: Maize Productivity, Organic Fertilizers, Inorganic Fertilizers, Integrated Nutrient Management, Soil Organic Carbon, Nutrient Use Efficiency, Nitrate Leaching, Greenhouse Gas Emissions, Sustainable Agriculture, Pakistan

1. Introduction

The global agricultural sector faces a definitive challenge in the twenty-first century: the requirement to escalate food production for a burgeoning population while simultaneously reversing the pervasive degradation of soil resources (Abbas et al., 2024). Maize (*Zea mays* L.), often heralded as the "miracle crop" and the "queen of cereals," stands at the epicenter of this struggle. Its inherent high genetic yield potential and adaptability across diverse agro-ecological zones make it a cornerstone of global food security, yet its productivity is inherently contingent upon high nutrient inputs (Erenstein et al., 2022). Traditionally, this demand has been met through the intensive application of inorganic fertilizers, which provide a concentrated and rapid supply of essential macronutrients nitrogen (N), phosphorus (P), and potassium (K) (Gram et al., 2020). However, the legacy of exclusive reliance on synthetic inputs is becoming increasingly visible in the form of soil acidification, declining soil organic matter (SOM), and a plateauing of yield responses (Deng et al., 2023). Conversely, organic amendments such as animal manures, composts, and biochar offer a pathway toward soil restoration, though they often lack the nutrient density and release speed necessary to support the peak physiological demands of modern maize hybrids (Abid et al., 2020). This report provides an exhaustive evaluation of the comparative effectiveness and the synergistic potential of organic and inorganic fertilizers, examining their influence on maize productivity, the complex biophysical dynamics of the pedosphere, environmental safety, and the socio-economic realities of global farming systems (Yigermal et al., 2019). The contrasting pathways through which organic and inorganic fertilizers influence maize systems are illustrated in figure 1.

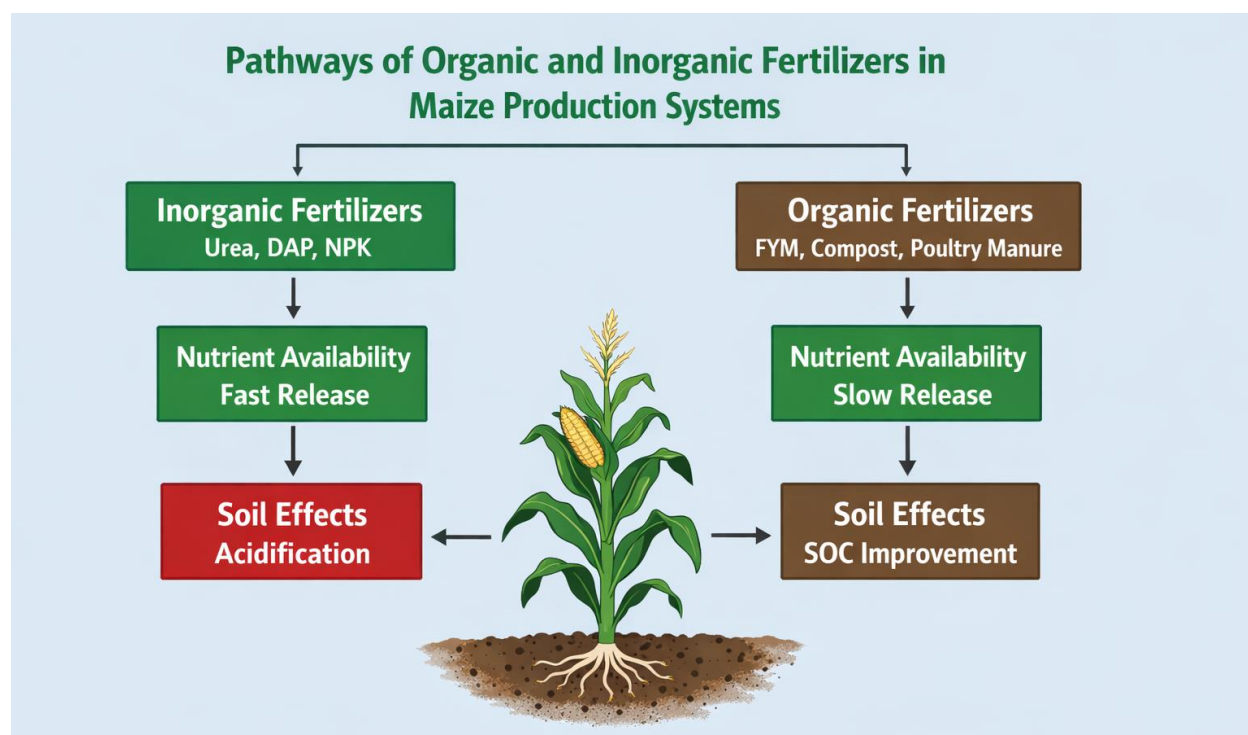


Figure 1: Pathways of Organic and Inorganic Fertilizers in Maize Production Systems

2. The Mechanics of Inorganic Fertilization in Maize Systems

Inorganic fertilizers represent the primary driver of the Green Revolution, accounting for approximately 50% of the total increase in modern crop yields. These chemically synthesized materials, such as urea (46.4% N), diammonium phosphate (DAP, 18% N and 20.09% P), and

potassium chloride (49.6% K), are designed for immediate solubility (Adiaha, 2017). This rapid availability is critical during the vegetative growth stages of maize, where nutrient uptake kinetics are at their peak (Bhandari et al., 2021).

2.1. Nutrient Uptake Kinetics and Nitrogen Use Efficiency

Nitrogen is the most limiting nutrient in maize production, serving as a fundamental component of chlorophyll, amino acids, and nucleic acids. Research indicates that omitting nitrogen fertilizer can lead to a staggering 41% decline in average maize yields (Fageria & Baligar, 2005). The efficiency of nitrogen addition is, however, highly variable and influenced by soil conditions and management practices. Meta-analyses reveal that nitrogen addition significantly increases maize yield by 50.26% to 55.72% (Du et al., 2020).

The timing of application is a critical determinant of this efficiency; for instance, topdressing at the jointing and tasseling stages (JS, TS) typically yields better results than single basal applications (Omara et al., 2019).

Despite their high concentration, inorganic fertilizers often exhibit low Nitrogen Use Efficiency (NUE), as only about 55% of global nitrogen application is actually absorbed by crops (Zhang et al., 2015). The remainder is prone to loss through ammonia volatilization, nitrate leaching, and denitrification, particularly in areas with high temperatures or excessive rainfall. The Partial Factor Productivity of Nitrogen (PFPN) serves as a key metric in this evaluation, defined as the ratio of grain yield to the amount of N applied:

$$\text{PFPN} = Y / N$$

In regions like sub-Saharan Africa (SSA), inorganic fertilizer use remains remarkably low, often less than 10 kg ha⁻¹ in some smallholder systems, due to high costs and poor market accessibility (Pasley et al., 2020). This disparity between the high nutrient demand of maize and low input levels results in "nutrient mining," where the crop extracts more nutrients than are returned to the soil, leading to a long-term decline in soil fertility (Zingore et al., 2015).

2.2. The Acidification and Degradation Pathway of Synthetic Inputs

The continuous application of ammonium-based fertilizers triggers a significant pedological shift through the nitrification process. This biochemical conversion of ammonium (NH₄⁺) to nitrate (NO₃⁻) releases hydrogen ions into the soil solution, progressively lowering the soil pH (Barak et al., 1997). In acidic soils, particularly those common in Ethiopia's maize belt or high-rainfall regions of Zambia, this acidification leads to aluminum (Al) and manganese (Mn) toxicity (Li et al., 2024). Aluminum saturation levels in these regions can range from 53% to 80%, often reducing maize yields to nearly zero by inhibiting root elongation and nutrient absorption (Abate et al., 2017).

Beyond chemical shifts, long-term inorganic fertilization often fails to maintain soil structural integrity. Unlike organic sources, synthetic fertilizers do not contribute to the soil organic carbon (SOC) pool directly (Khan et al., 2007). While they may increase SOC indirectly by promoting higher biomass production (decaying roots and crop residues), the net effect is often a loss of soil structure and a reduction in microbial biodiversity (Hu et al., 2023). A meta-analysis comparing land-use types found that while inorganic fertilization increases biomass by 42%, it simultaneously causes an 18% decline in plant species richness and a 6% decline in evenness, a tradeoff that is largely avoided in organic systems (Murphy, 2015).

3. Organic Amendments: Restoration of the Pedological Foundation

Organic fertilizers, derived from animal residues, plant biomass, or recycled waste, offer a fundamentally different approach to nutrient management. They act as slow-release reservoirs,

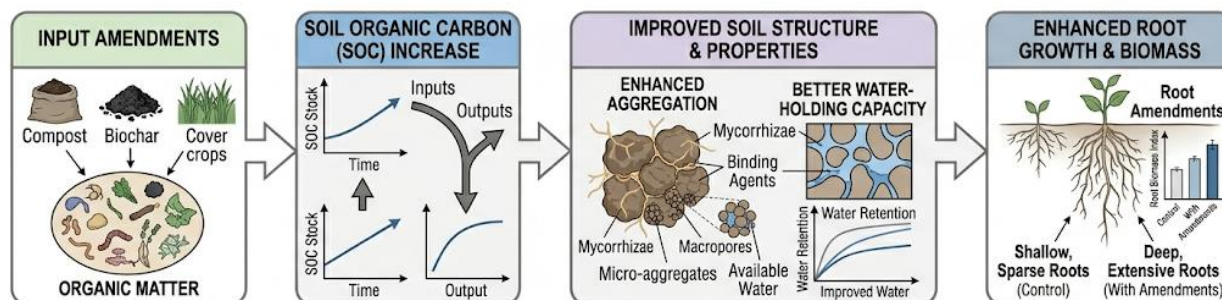
providing a diverse array of macro- and micronutrients including magnesium, calcium, zinc, and iron, which are often absent in standard inorganic blends (Zubair et al., 2023).

3.1. Structural Stabilization and Carbon Sequestration Dynamics

The primary value of organic amendments lies in their capacity to improve the soil's physical architecture. Materials such as farmyard manure (FYM), poultry manure (PM), and compost introduce organic matter that binds soil particles into stable aggregates (Hati et al., 2006). Long-term studies (spanning 36 years) demonstrate that integrated organic-inorganic treatments significantly enhance the SOC pool (Bhattacharyya et al., 2010). For example, in a maize-wheat rotation, the SOC pool reached its highest value of 11.6 Mg ha⁻¹ with the application of 100% NPK + FYM, compared to only 7.3 Mg ha⁻¹ in unfertilized controls (Brar et al., 2013).

This increase in SOC is directly correlated with improved physical properties. Aggregate Mean Weight Diameter (MWD), a proxy for structural stability, increased from 0.31 mm in control plots to 0.52 mm in high-organic treatments (Sodhi et al., 2009). This structural improvement enhances the soil's dual-porosity system: macropores facilitate rapid water infiltration, while micropores increase the water-holding capacity (WHC) (Rasool et al., 2008). Research in northern China indicates that organic fertilizer application alone can increase soil moisture by 3.59%, making maize more resilient to water stress during critical growth stages like tasseling or silking (Liu et al., 2020). Figure 2 demonstrates how organic amendments improve soil structure and carbon dynamics.

Figure 2: Role of Organic Amendments in Soil Structure and Carbon Sequestration



3.2. Bio-organic Fertilizers and Microbial Symbiosis

The biological vitality of the soil is heavily dependent on the carbon substrates provided by organic fertilizers. These amendments support a complex food web of microorganisms and soil fauna (Bamdad et al., 2022). Long-term organic incorporation has been shown to improve soil fauna feeding activity by 35.2% to 42.5%. Furthermore, organic fertilizers stimulate the activity of key soil enzymes such as beta-1,4-glucosidase, sucrose, and urease, which are essential for the mineralization of carbon and nitrogen (Zhuang et al., 2024).

Recent trends have seen the rise of specific "bio-digestates" or liquid biofertilizers, such as those derived from *Moringa oleifera* or *Momordica charantia*. These bioles are rich in phytohormones and beneficial microbes, which promote vigorous seedling development and physiological resilience (Tejada-Rodríguez et al., 2025). Studies in Kazakhstan have shown that specialized organic fertilizers can increase the quality of maize grain, improving fat, protein, and starch content by 35%, 22%, and 8%, respectively, while simultaneously enhancing the fatty acid composition (Toishimanov et al., 2024).

4. Integrated Nutrient Management (INM): The Synergistic Frontier

Given the rapid response of inorganic fertilizers and the structural benefits of organic amendments, the paradigm of Integrated Nutrient Management (INM) has emerged as the most viable strategy for sustainable maize intensification. INM aims to synchronize nutrient release with crop demand while maintaining long-term soil health (Sun et al., 2023).

4.1. Synchronicity of Nutrient Release and Plant Demand

The fundamental challenge in maize nutrition is the mismatch between the rapid nutrient requirements of the plant and the slow mineralization of organic matter. INM addresses this by using inorganic inputs to meet early-stage requirements and organic sources to sustain the plant through later stages of grain filling (Lawal et al., 2021). This combination leads to a more balanced supply of nutrients throughout the growth cycle, reducing the risk of "hunger periods" that can occur with slow-release organic sources alone (Bhandari et al., 2021).

The synergistic effect of INM is particularly evident in plant physiological metrics. Integrated treatments often produce the tallest plants and largest leaf areas. For instance, a poultry manure + NPK (PM+NPK) treatment produced maize plants with a height of 212 \pm 10.6 cm and a leaf area of 3,250 cm^2 , significantly outperforming sole inorganic treatments and sole organic treatments (Annual Methodological Archive Research Review, 2025). This enhanced vegetative vigor translates into higher photosynthetic efficiency and greater biomass accumulation (Shi et al., 2020).

Table 1. Comparison of Maize Productivity and Soil Health Indicators across Fertilization Regimes.

Treatment Parameter	Control (CK)	Sole Inorganic (NPK)	Sole Organic (PM/FYM)	Integrated (PM+NPK)	Source
Grain Yield (t ha^{-1})	3.01 \pm 0.15	3.8 \pm 0.19	3.5 \pm 0.17	4.3 \pm 0.21	
1000-Grain Weight (g)	270 \pm 13.5	290 \pm 14.5	285 \pm 14.2	305 \pm 15.2	
Soil Organic Matter (%)	0.95 \pm 0.05	0.90 \pm 0.05	1.25 \pm 0.06	1.35 \pm 0.07	
Microbial Biomass (mg C/kg)	280	315	395	413	

4.2. Meta-Analytical Quantifications of the Integrated Approach

Global meta-analyses confirm that the combined application of chemical and organic fertilizers yields the greatest increase in both productivity and water use efficiency. In northern China, replacing 20% to 30% of chemical fertilizers with organic counterparts has been shown to stabilize wheat-maize yields while improving soil availability and organic matter (Frontiers, 2022; Yameogo et al., 2022). Long-term simulations (26 years) suggest that an optimal ratio for maintaining high yields while minimizing emissions is a 1:1 or 3:2 organic-to-inorganic nitrogen ratio (Shi et al., 2024). Specifically, a 60% organic nitrogen substitution resulted in a yield of 12,578 kg ha^{-1} , which was 20.10% higher than sole inorganic application (Wang et al., 2025). The resilience of INM systems is also superior under abiotic stress. In semi-arid regions, the increased soil moisture and structural stability under INM allow maize to adapt better to "poor soils" and erratic rainfall (Sharan Kumar et al., 2017). This is critical as climate change increases the

frequency of drought events during the maize flowering stage, which is the most sensitive period for yield loss (Jing et al., 2023).

5. Pedological Transformations: Physical, Chemical, and Biological Dimensions

A deep dive into the pedological transformations under different fertilization regimes reveals why the integrated approach is fundamentally superior. The soil is not a passive medium but a dynamic biological entity that responds to the chemistry and physics of added amendments (Mnukwa et al., 2025).

5.1. Soil Physical Properties: Infiltration, Porosity, and Aggregation

Maize productivity is heavily reliant on the soil's ability to transmit and store water. Long-term inorganic fertilization can lead to soil compaction and reduced porosity. In contrast, organic amendments lower soil bulk density and improve aggregation through the secretion of microbial "glues" such as glomalin and other polysaccharides (MDPI, 2015).

The quantitative impact on water dynamics is profound. Cumulative infiltration rates are significantly higher in soils with a history of organic or integrated fertilization. In a 36-year trial, cumulative infiltration after 360 minutes was 71.7 cm in the 100% NPK + FYM treatment compared to only 53.9 cm in the control (Mayer, 2023). This increased infiltration reduces surface runoff and erosion, which are major factors in soil degradation in tropical and semi-arid environments (ABUAD Journal, 2025).

5.2. Chemical Buffering and Cation Exchange Capacity

The chemical environment of the soil determines the bioavailability of nutrients. Organic fertilizers enhance the Cation Exchange Capacity (CEC), which is the soil's ability to hold onto positively charged ions like K^+ , Ca^{2+} , and Mg^{2+} (Liu et al., 2024). This increased CEC prevents the leaching of vital nutrients and provides a chemical buffer against pH shifts (Khan et al., 2024).

In acidic soils, the role of organic matter is even more vital. Biochar, for example, is highly effective at neutralizing soil acidity by releasing basic cations and increasing the pH buffering capacity (Huang et al., 2023). This neutralization reduces the solubility of aluminum, thereby alleviating toxicity and allowing maize roots to explore deeper soil layers for water and nutrients (Mosharrof et al., 2021). The efficacy of such treatments is often measured by the Membership Index (Fi) for aluminum tolerance, where genotypes are ranked from Rank 1 (highly tolerant, $Fi \geq 0.8$) to Rank 5 (highly susceptible, $Fi < 0.2$) (Al-Ashkar et al., 2019).

Table 2. Soil Physicochemical Properties under different Fertilization Strategies.

Soil Property	Control	Sole Inorganic	Sole Organic	Integrated	Source
Soil pH	7.8 \pm 0.4	7.6 \pm 0.38	7.9 \pm 0.4	7.7 \pm 0.39	
Available N (mg/kg)	0.11 \pm 0.01	0.13 \pm 0.01	0.12 \pm 0.01	0.15 \pm 0.01	
SOC Pool (Mg ha ⁻¹)	7.3	8.1	10.4	11.6	
Aggregate MWD (mm)	0.31	0.35	0.48	0.52	

5.3. Enzymatic Activity and Biological Vitality

The productivity of a crop is mirrored by the enzymatic activity of its soil. Urease facilitates the hydrolysis of urea into ammonia, while dehydrogenase acts as a marker for the metabolic activity

of soil microorganisms (Sun et al., 2023). Research shows that while sole inorganic fertilization may provide the substrate for enzymes like urease, it often fails to support the microbial biomass necessary to sustain high enzymatic rates over time (Ćirić et al., 2023). Integrated PM+NPK treatments have shown dehydrogenase activity levels of 36 units, significantly higher than sole inorganic (28) or sole organic (32) treatments (Tusar et al., 2023).

6. Environmental Impact Assessments: Leaching and Gaseous Flux

The comparative environmental footprint of fertilizers is a pressing global issue. Nitrogen losses represent both an economic waste and a threat to water security (Penuelas et al., 2023).

6.1. Nitrate Leaching and Groundwater Safety

Nitrate (NO_3^-) is highly mobile and prone to leaching, leading to eutrophication of surface water bodies. Excessive inorganic nitrogen application is a primary cause; in Nigeria, sole chemical fertilization resulted in nitrate runoff concentrations of 32.4 mg/L (E3S Web of Conferences, 2024). Integrated systems offer a solution; substituting inorganic nitrogen with organic sources reduces nitrate leaching. A 100% replacement (sole organic) can reduce nitrate nitrogen leaching by up to 42.6% (Biernat et al., 2020).

6.2. Greenhouse Gas Flux: Nitrous Oxide and Methane Dynamics

Maize production contributes to global nitrous oxide (N_2O) emissions. N_2O emissions are generally highest under sole inorganic fertilization and decrease as the proportion of organic fertilizer increases (Hu et al., 2023). A study in northern China found that a 75% organic fertilizer substitution (75%OF) resulted in N_2O emissions that were 187.3% lower than conventional inorganic fertilization (Hao et al., 2025).

Table 3. Comparative Environmental Footprint of Nitrogen Management.

Environmental Metric	Sole Inorganic (NP)	50% Organic (50%OF)	75% Organic (75%OF)	Source
Nitrate Leaching (mg/L)	32.4	24.1	18.2	
N_2O Emissions	Baseline (High)	Moderate	187.3% Lower	
GWP Ranking (1=Worst)	1	2	5	

7. Socio-Economic Feasibility for Smallholder Agronomy

Despite agronomic advantages, adoption is governed by economic reality. For smallholder farmers, accessibility and return on investment are paramount (Llewellyn & Brown, 2020).

7.1. Economic Returns: Benefit-Cost Ratios and Gross Margins

Inorganic fertilizers are frequently the most expensive input for farmers in sub-Saharan Africa. However, comparative economic analysis suggests that while inorganic NPK might produce the highest absolute grain yield, organic amendments often yield higher Benefit-Cost Ratios (BCR) and net profits due to lower input costs (Lawal et al., 2021). In Nigeria, the application of a Moringa-banana peel-maize stalk (MBM) organic fertilizer resulted in a BCR of 15.16, significantly higher than synthetic NPK. Similarly, in Benue State, the mean gross margin for maize produced with organic fertilizer was N123,680, compared to N33,719 for inorganic fertilizer (Abah et al., 2022).

Table 4. Economic Indicators for Maize Production across various Regions.

Treatment/Region	Input Cost (Relative)	Net Benefit/Profit	BCR	Source
NPK (Nigeria)	High	N495,600	8.51	
Organic MBM (Nigeria)	Low	N405,400	12.35	
Organic (Benue State)	Low	N123,680	High	

7.2. Adoption Barriers: Labor and Policy Frameworks

The primary constraint to organic fertilizer adoption is its bulky nature, which requires significant labor for transport and application. In contrast, inorganic fertilizers are concentrated and easy to apply (Bhandari et al., 2021). Policy interventions, such as Tanzania's National Agricultural Input Voucher Scheme (NAIVS), have attempted to bridge the accessibility gap, but gains are difficult to sustain once subsidies are removed (Zhuang et al., 2024).

8. Technological Frontiers: Biochar, Nano-fertilizers, and Bio-stimulants

Next-generation management move toward specialized amendments that offer precision delivery with soil-building properties (Murphy, 2015).

8.1. Biochar and Carbon-Negative Agriculture

Biochar is stable for centuries and improves soil CEC and water retention while serving as a mechanism for carbon sequestration. In Ghana, an integrated biochar + compost + chemical fertilizer treatment increased maize yield by up to 127.4% compared to controls, while improving soil organic carbon by 115.8% (Abdul-Aziz & Haruna, 2025).

8.2. Nano-fertilizers and Precision Delivery

Nanotechnology represents the frontier of nutrient delivery. Nano-fertilizers offer targeted delivery with minimal loss (Brar et al., 2013). Research in India demonstrated that a 75% recommended dose of conventional fertilizer, supplemented with nano-N and nano-P foliar sprays, consistently showed superior performance (Zubair et al., 2023). This approach achieved an agronomic efficiency of nitrogen (AEN) of 67.9%, showcasing the potential to reduce conventional fertilizer requirements by 25% (Bhanuprakash et al., 2024).

9. Conclusions

Comparative evaluation of organic and inorganic fertilizers in maize production reveals a clear trade-off between short-term yield maximization and long-term sustainability. While inorganic sources deliver rapid, high nutrient availability and superior immediate grain output, their exclusive use accelerates soil organic matter depletion, disrupts microbial communities, increases nitrate pollution risk, and contributes disproportionately to agricultural N₂O emissions. Organic amendments, though slower to release nutrients, rebuild soil health elevating SOC, enhancing microbial activity, improving physical structure, and boosting nutrient retention while integrated strategies consistently achieve comparable or only marginally lower yields with markedly better environmental and economic profiles. In Pakistan's context, where maize occupies diverse agro-ecological zones and smallholder farmers face rising input costs alongside soil fertility decline, INM approaches (e.g., 50–75% inorganic N substituted with compost, FYM, or green manure) emerge as the most pragmatic and resilient pathway forward. These systems not only sustain productivity but also reduce fertilizer dependency, lower production costs, improve water and nutrient efficiency, and enhance climate adaptation through better soil resilience to drought and heat stress. Scaling adoption requires overcoming persistent barriers: farmer education on composting techniques and long-term benefits, development of cost-effective organic supply

chains, localized calibration of organic–inorganic ratios across soil types and seasons, and supportive policies (subsidies for biofertilizers, soil health cards, extension on INM packages). By prioritizing integrated nutrient management informed by rigorous field research, Pakistan can secure maize yields, restore degraded soils, reduce environmental externalities, and align the crop's intensification with national goals for sustainable agriculture and climate resilience ensuring food security and rural livelihoods for future generations.

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