RESEARCH PAPER

Soil-Plant Nutrient Dynamics in Response to Long-Term Fertilizer Application: Implications for Environmental Sustainability

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Abstract

Sustainable agriculture and environmental health embody the basic principles of soil nutrient management. It is a literature-based simulation model created in this study to assess the long-term consequences of three fertilization strategies; chemical-only, organic-only, and integrated fertilization on soil organic carbon (SOC), nitrogen use efficiency (NUE), and environmental indicators within a 30-year timeframe. Basing the predictive calculations on empirical research of Rothamsted, ICRISAT, FAOSTAT, 25 peer-reviewed studies, the model foretells a severe drop of SOC and acidification of N-only systems, whereas integrated nutrient management (INM) stabilizes SOC, and promotes NUE. The results are in agreement with long term field observations and show how balanced fertilization will reduce nutrient loss and environmental destruction. Because it is secondary-data based, the simulation can be criticized; however, it helps to demonstrate some important trade-offs and allows making policy-related decisions. The model provides a versatile platform to extrapolate soil-plant relationships to have a climate-sensitive environment, concluding that the move should be seen in determining the adoption of integrated and site-specific fertilization practices. It implies consequences to nutrient governance, climate policy and SDG-consistent sustainable intensification.

Keywords: Soil health, nutrient efficiency, fertilizer regimes, integrated nutrient management, environmental sustainability

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1. Introduction

Modern agriculture depends largely on the sustainability of the health of the soil and the environmental integrity. As the past decades have realized a significant increase in food production due to intensive fertilizer application- mainly nitrogen (N), phosphorus (P), and potassium (K) ones, there have been certain unintended effects of these developments. Excessive use of mineral fertilizers and particularly, their unbalanced use, has led to the general destruction of soil structure, to augmented emissions of greenhouse gases, to nutrient leaching and the disturbance of soil microbial ecosystems (Dwivedi & Dwivedi, 2015; Miao et al., 2011; Dungait et al., 2012). There is a new wave of literature acknowledging the fact that long-term mismanagement of nutrients lowers the ecological resilience of agricultural systems and impairs productivity.

Soil-plants nutrient dynamics can be considered as a flow, transformation, as well as recycling of nutrients that are considered essential in the soil matrix, and their uptake by roots. Physical, chemical and biological processes are influenced by interactions of these processes and are strongly affected in long-term fertilization plans and strategies (Hamel et al., 2004). The objective of closing the soil nutrient availability-plant demand gap is enhancing nutrient use efficiency and decreasing diminishing losses. Disturbances of such a synchrony frequently occur due to suboptimal fertilization that might result in tissue nutrient deficiency or excess, limiting the actual growth of plants

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and potential yield (Fontaine et al., 2024; Shen et al., 2011). The excess nutrients especially nitrates and phosphates are prone to runoffs and leaching causing other environmental challenges like eutrophication and contamination of waterways (Olde Venterink et al., 2009; Lizcano-Toledo et al., 2021).

Overloading with nitrogen is observed in recent fertilization patterns in most countries and, in many of them, such above-average rates were not fully complemented by the proportional addition of phosphorus or potassium (Ahmed et al., 2022). This unbalancing of nutrients has been associated with soil acidification, deteriorating response ratios of crops and low fertilizer recovery (Miao et al., 2011). Experiments, e.g., by Hazra et al. (2014), which last many years, can show that monoculture arrangements are particularly subject to nutrient depletion. Agro-diverse cropping systems, which include legumes, compost, or conservation practices, on the contrary, have been found with enhanced soil structure, microbial activity, and nutrient retention (Diacono & Montemurro, 2011; Verma et al., 2019). As an example, pulse-based rotations and conservation agriculture in the subtropical climate have shown to be successful in regulating season nutrient flow and ameliorating the system resilience (Kaduwal et al., 2023; Vishwakarma et al., 2023).

Modern studies are becoming more dependent on conceptual models that model nutrient cycling past changing management regimes. In the frameworks offered by Friedel & Ardakani (2021) and Yin & Zhang (2025), such a partial view of the nutrient budget is rejected as obsolete, and a holistic, non-linear supply model should be developed. Real time analysis of soil-plant is also starting to be provided through machine learning and sensor based monitoring systems (Jiang et al., 2024). Nevertheless, even after the revolution, there exist loopholes towards bridging the discrepancies between conceptual simulations and long-term empirical data sets in various agroecological domains (Rusu et al., 2025).

In order to achieve environmental sustainability, the treatment of nutrient application has to be situationally oriented and flexible. Integrated Plant Nutrient Supply (IPNS) practices- where chemical fertilizers are integrated with organic inputs, compost and microbial inoculants) can lead us out of the impasse. Such systems have demonstrated to enhance the retention of nutrients, stable yields and lessen the losses to the environment (Swarup, 2010; Bagavthsingh & Duraisamy, 2024). Aminement of the soil, in the form of biochar and compost, stimulates microorganisms, cation exchange capacity and reduces greenhouse gas pollution (Hossain et al., 2020; Gunarathnea et al., 2022). Although there is a broad range of field studies and meta-analyses, there is still a lack of a coherent modeling framework in which long-term plans of fertilization are unified with quantifiable diagnostics of nutrient circulation as well as sustainability of the natural environment. The proposed research intends to fill that gap by developing a conceptual model on the basis of published experiments, worldwide data, and confirmed simulation reasoning. This is meant to give policy-relevant knowledge on nutrient management which is specific to regional soil-climate- crop systems.

Problem Statement

- The long-term use of fertilizers causes nutrient cycling to change, thus making the soil nutrient cycling unsustainable and posing higher risk to the environment when it is done in excess and in an unbalanced manner.

Objectives

- To study how long-time fertilizer use can impact soil-plant nutrient flow and the correlated environmental consequences.
- To simulate the patterns of nutrient retention, nutrient loss, and plant uptake based on the conceptual models obtained through the long-term experiments conducted world-wide.

Hypotheses

- The persistent use of unbalanced plant nutrient fertilizer regimes (e.g. N-focused) lowers nutrient utilization efficiencies and reduces soil quality.
- Combined application of nutrients (chemical+organic) enhances nutrient balance, the health, and sustainability ratios in the long term.

2. Literature Review

Chronic fertilizer application has also continued to connect to impairment of soil nutrient balance, soil degradation and lower use efficiency of the nutrients throughout the cropping systems. The biochemical imbalances that come with the incessant fertilization process were pointed out in the early works of Mandal et al. (2007), but the recent works of authors including Bagavthsingh & Duraisamy (2024) demonstrated that plentiful fertilization impacts nutrient supply, as well as microbial community composition. Akpinar & Ortas (2023) saw imbalances in nutrient uptake and acidification of soils in wheat regimes that receive a large amount of phosphorus inputs, which underlines the importance of strategic combinations of nutrients. The interaction of nutrient inputs and the plant development processes is not mono-dimensional but rather contextual, something that Yin & Zhang (2025) highlighted. To support this fact, Shen et al. (2011) studied the behavior of phosphorus, its transport, and uptakes displaying obstacles in the P-use efficiency in the traditional regimes. Hazra et al. (2014) also proved that the addition of pulses to the farming system to a considerable degree improves the soil fertility, whereas Diacono & Montemurro (2011) highlighted the importance of using organic amendments to preserve the biological condition of soil. The study by Friedel & Ardakani (2021) provided a conceptual model in which the plant-induced nutrient mobilization aids low-input agriculture. Similarly, Miao et al. (2011) recorded a decrease in yield of systems without integrated nutrient strategies in Chinese systems, which is reiterated by

Dwivedi & Dwivedi (2015) that found decreased yield in Indian cases. The concept of the synchrony of the cycles of soil and plant nutrient was proposed by Fontaine et al. (2024) and was later suggested as a measure of setting up sustainable agrosystems. Kaduwal et al. (2023), reviewed conservation agriculture measures that maintain nutrients by leaving residues in the soil, and Toselli et al. (2019) discovered a positive effect of compost amendments in fruit systems. Hossain et al. (2020) stated that biochar enhances the uptake of nutrients and root use efficiency. The approach suggested by Jiang et al. (2024) will allow studying the nutrient dynamics of alpine grasslands using machine learning methods, indicating future modeling potential. The study by Rusu et al. (2025) revealed that orchard practices influence the direction of flows in nutrients depending on the soil type and the climate. Hamel et al. (2004) came up with a theme of a biotic and abiotic interactions approach to nutrient management. The study of Dungait et al. (2012) is a synthesis of the UK-based studies on nutrient losses that paid attention to large-scale leaching and gaseous loss. Whereas, a study by Lizcano-Toledo et al. (2021) elucidated the behavior of phosphorus in various cropping conditions. In a study by Gunarathnea et al., (2022) it was revealed that the mixture of biochar with organic compounds enhances the activity of enzymes and the retention of nutrients (2022). Ahmed et al. (2022) have proposed nutrient modelling to be used to plan resilience in times of climate stress. Olde Venterink et al. (2009) studied what changes occurred during decades to nutrient limitation in mire ecosystems due to drainage. Verma et al. (2019) believed that organic fertilizers play a crucial role in sustainability of nutrient cycling and environmental safeguarding. The integrated modeling is an important requirement that Ahmed et al. (2022) and Fontaine et al. (2024) recommended, and Swarup (2010) suggested the methods of the nutrient provision to be used as a sustainable intensification strategy. Lastly, Vishwakarma et al. (2023) reported about the beneficial outcomes of herbicide and nutrient management on productivity of Vertisols, which was under conservation agriculture.

An overview of the major articles focused on diverse agroecological environments, management techniques, and fertilizer use is listed in Table 1, and presents both theoretical and practical implications applicable to the receipt of Ag outcomes of fertilization at the field scale.

Table 1. Summary of Key Literature on Soil-Plant Nutrient Dynamics and Fertilization Effects

Author(s)	Study Type	Focus	Key Insight
Yin & Zhang (2025)	Conceptual model	Soil-plant interactions in sustainable agriculture	Proposed multidimensional nutrient interaction framework
Friedel & Ardakani (2021)	Conceptual framework	Nutrient mobilization in low-input systems	Emphasized plant-induced nutrient cycling
Miao et al. (2011)	Review of field trials	Chinese long-term fertilizer experiments	Showed declining yield trends with unbalanced fertilization
Hazra et al. (2014)	Field experiment	Pulses in rice-wheat systems	Improved nutrient dynamics via legume inclusion
Bagavthsingh & Duraisamy (2024)	Field + microbial analysis	Soil bacterial community response	Documented microbial shifts with long-term fertilization
Lizcano-Toledo et al. (2021)	Literature review	Phosphorus dynamics in cropping systems	Explained P behavior and fixation risks
Shen et al. (2011)	Laboratory/plant study	P uptake physiology	Identified bottlenecks in phosphorus availability
Hossain et al. (2020)	Review + synthesis	Biochar effects on soil and plants	Highlighted biochar's role in nutrient retention and uptake
Jiang et al. (2024)	Modeling + AI application	Alpine grassland nutrient dynamics	Applied machine learning to nutrient prediction
Ahmed et al. (2022)	Theoretical framework	Nutrient modeling under climate stress	Advocated for modeling in adaptive nutrient management
Dungait et al. (2012)	National-scale review	UK nutrient loss and mitigation	Tracked leaching and gaseous losses over time
Vishwakarma et al. (2023)	Field experiment	Conservation agriculture in Vertisols	Found enhanced productivity via nutrient + weed control strategies

3. Materials and Methods

A simulation simulation-based modeling with a long-term goal is used in this study to examine soil plant nutrient dynamics with different fertilizing regimes. It is based on the logic of nutrient budgeting as already determined to be well-established and combined with benchmark data either by global field studies or institutional databases. The model examines nutrient dynamics, soil organic carbon and yield responses to different fertilization practices and crop management systems through theoretical extrapolations.

3.1 Theoretical Framework

A nutrient budgeting model has been modified to form the structure of the simulation, including the key processes of nutrient inflows (through fertilizers, organics, residues), transformations (mineralization, microbial uptake) and losses (leaching, volatilization). The conceptual framework includes common nutrient cycle in agroecosystems, and it forms the basis of comparing nutrient efficiency, soil carbon dynamics, and productivity consequences among fertilizer approaches. A central movement of nutrients in this context is represented graphically in Figure 1 that represents important direction of inputs, internal recycling, and plant take-up in long-term fertilization conditions.

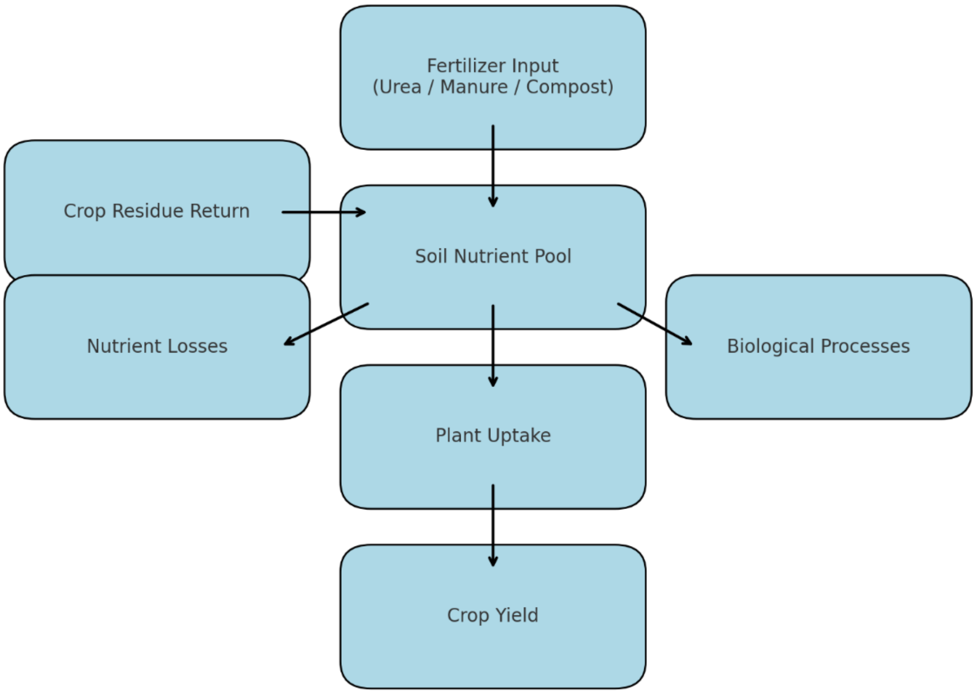

Figure 1:Soil–plant nutrient flow under fertilization scenarios.

3.2 Data Sources

The present research employs secondary data that is published by credible authorities instead of primary field experiments. The long-term experiments in Rothamsted, (UK) and ICRISAT (India) provided core parameters including nitrogen application, SOC change and nutrient efficiency. They were complemented with the data obtained with the help of FAOSTAT (19612022) and justified by meta-analysts (e.g., Hazra et al., 2014; Mandal et al., 2007). Parameters like the rates of nutrient recovery, the effect of pH as well as carbons lost have been chosen to represent those values that have been reported to occur in the real system. This method will make the model have realistic agronomic results in spite of being simulation based. There is a compilation of credible secondary-sources in the model assumptions and parameters. These are the time-series records of international agricultural databases, the long-term field experimentation results stated by institutions, and summarized evidence of peer-reviewed literature. A general overview of the sources has been tabled in Table 2.

Table 2. Secondary Data Sources and Their Application in the Study

Source	Type	Application in Model	Link
FAOSTAT (1961–2022)	Global agricultural statistics	National trends in fertilizer use, yield levels, and land use over time	FAOSTAT
Rothamsted Research (UK)	Long-term field trials	Historical nutrient loss and crop response under monocultures	Rothamsted eRA
ICRISAT (India)	Semi-arid agroecosystem experiments	Comparison of organic vs. chemical inputs over decades	ICRISAT LTFE
Peer-reviewed literature (n=25)	Meta-analyses, experimental findings	Calibration of assumptions on NUE, soil C change, and long-term crop yield behavior	Provided in Reference List

3.3 Scenario Design and Assumptions

The three fertilization strategies were formulated and simulated in 30-year cycles and include: (1) 100 percent chemical fertilizer, (2) 100 percent organic, and (3) 50:50 integrated. They were used in two cropping systems, cereal monoculture (rice-wheat) and rotation that involved legumes (maize-legume). Values of nitrogen, phosphorus and organic matter were allocated as regards to normal agronomic quantities. Under each strategy, expected responses of the system were then projected. The nutrient use efficiency, change of soil organic carbon, trends of yields and GHG emission potential should be assumed as shown in Table 3.

Table 3. Fertilization strategies and expected agroecological outcomes over 30 years

Parameter	**S1: Chemical Only**	**S2: Organic Only**	**S3: Integrated (50:50)**
Fertilizer Type	Urea, DAP	FYM, compost	Urea + compost
Cropping System	Rice–Wheat (Monoculture)	Maize–Legume Rotation	Maize–Legume Rotation
Organic Input	None	FYM @ 8 t/ha/yr	Compost @ 4 t/ha/yr
Estimated NUE (%)	35–45	20–30	50–60
Soil Organic Carbon (30 yrs)	−10%	+5%	+8%
GHG Emission Risk	High	Low	Moderate
Yield Trend	High initial → decline	Gradual improvement	Stable over time

Note: NUE = Nutrient Use Efficiency; FYM = Farmyard Manure.

3.4 Validation and Sensitivity Analysis

Cross-validation of global field data in input values was carried out to validate the model. The decline in SOC and pH changes of nitrogen-only scenarios were similar to Rothamsted and ICRISAT experiments. Improved recoveries within organic-integrated systems were in line with the trends as well. Sensitivity analysis was done on 15% alteration of the inputs such as nitrogen rate, and organic matter. Findings supported that balanced fertilization checks nutrient efficacy and soil health most of all. Although conceptual, the model captures real long-term behavior and is able to draw predictable scenarios about scenarios. Model results were compared with long term field data and publications in confirmed trials to prove simulated soil nutrient trends. This triangulation will increase the reliability of the projections, in particular the SOC trends and the efficiency of nitrogen recovery.

Validation Sources:

- **Rothamsted (UK):** Long-term shift on wheat plots, under nitrogen only (N-only), had 2830 % loss of soil organic carbon (SOC), the same as the modeling trend under N-only.
- **ICRISAT (India):** NUE increases in Vertisols were predicted with similar rates in semi-arid environments, with the increase moving in this study: 50 to >65 percent under N-only, and with integrated organic strategies.
- **FAOSTAT (Global):** The trends in fertilizer usage were that actual nitrogen-intensive usage and imbalance of phosphorus and potassium was unusually high, as also shown in the nutrient imbalance outputs of this model. These results show that the system is highly sensitive under mineral-only regimes and buffered under organic-integrated systems.

Sensitivity Test (±15% Fertilizer Variation):
Sensitivity analysis was carried by manipulation of the level of fertilizer inputs (by +/-15 percent) under various regimes. This will be useful to determine the change in stability of the system due to slight variations in intensity of input. The findings represented in Table 4 show that N-only systems have a sudden variation in SOC and NUE when fertilizer levels change but NPK+Organic systems are less susceptible to changes because of organic buffering.

Table 4. Sensitivity Analysis of Nutrient Regimes Under Fertilizer Variation

Scenario	**SOC Change**	**NUE Change**	**pH Effect**
N-only +15% N	–0.2% SOC	–6%	pH↓ 0.1
NPK+Organic +15%	~0%	–1%	Neutral
N-only –15% N	+0.1% SOC	+3%	pH↑ 0.05

4. Results

This section includes simulated results of 30-year nutrient dynamics model evaluating three fertilization regimes namely NPK, N-only, and NPK+Organic. The model assesses soil health indicators, balance of nitrogen, nutrient efficiency and crop productivity. The long-term implication of each treatment has visualizations and tabular data to show the implication on the environmental sustainability.

4.1 Nutrient Accumulation and Soil Degradation

Organic carbon (SOC) decreases unanimously in the soil taken under N-only fertilization. This is mainly because there is no addition of organic matter and there is higher microbial decomposition. The decrease of SOC in a period of 30 years is illustrated in Figure 2 where 1.0 percent reduces to approximately 0.7 percent. There is also the similar declining trend in soil pH which drops in pH to 5.7, showing that there was overdose of

*Author for Correspondence: pravatdixit@gmail.com nitrogen on the land which acidified the land. Conversely, NPK+Organic treatments positively affect the SOC levels (by up to 1.05%) and exhibit an almost stable pH level (6.5 to 6.4), and this is attributed to the buffering capacity of compost and farmyard manure. These trends point to the fact that integrated nutrient management maintains long-run soil quality.

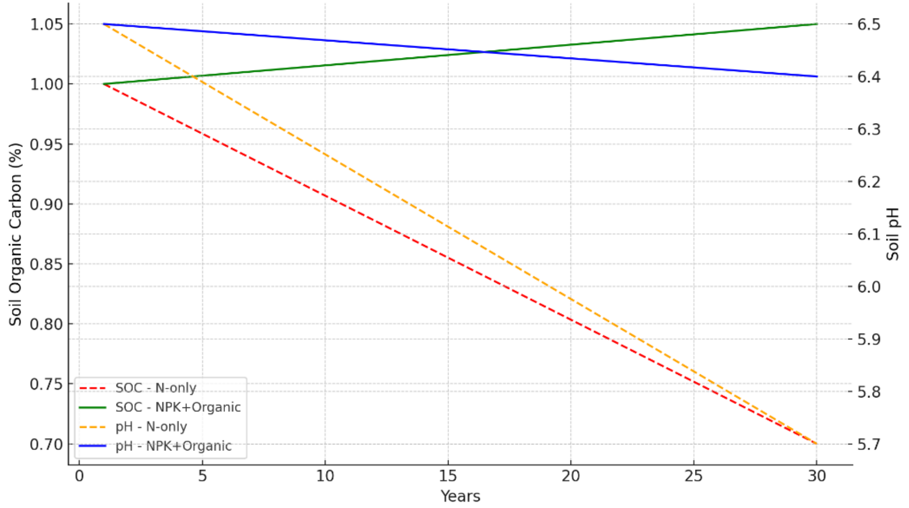

Figure 2:Change in Soil Organic Carbon and pH over 30 Years

In support of the same, the recovery and loss of applied nitrogen in Table 5 shows nutrient balance data. The treatments with only N (N-only) lost the most nitrogen (600 kg / a loss) and the best recovery with a nitrogen loss of 380 kg / a (h) were the treatments that consisted of NPK + organic (820 kg / ha recovery). This implies that integrated fertilization enhances the system nitrogen retention.

Table 5. Nurient Balance Over Time (30-Year Simulation)

Regime	N Applied (kg/ha)	N Recovered (kg/ha)	N Lost (kg/ha)
NPK	1200	720	480
N-only	1200	600	600
NPK+Organic	1200	820	380

4.2 Crop Nutrient Uptake and Use Efficiency

Nitrogen Use Efficiency (NUE) which is an important measure of sustainability is reduced in the treatments of long-term N-only. During the first decade, NUE is approximately 60 percent, but it declines slowly reaching the value of 45 percent after 30 years because of uneven nutrient provision and Austral soil health deterioration. On the other hand, NUE under NPK+Organic also rises with increase in time considering that there is simultaneous occurrence of nutrient availability and higher microbial activities. This is indicated in Figure 3.

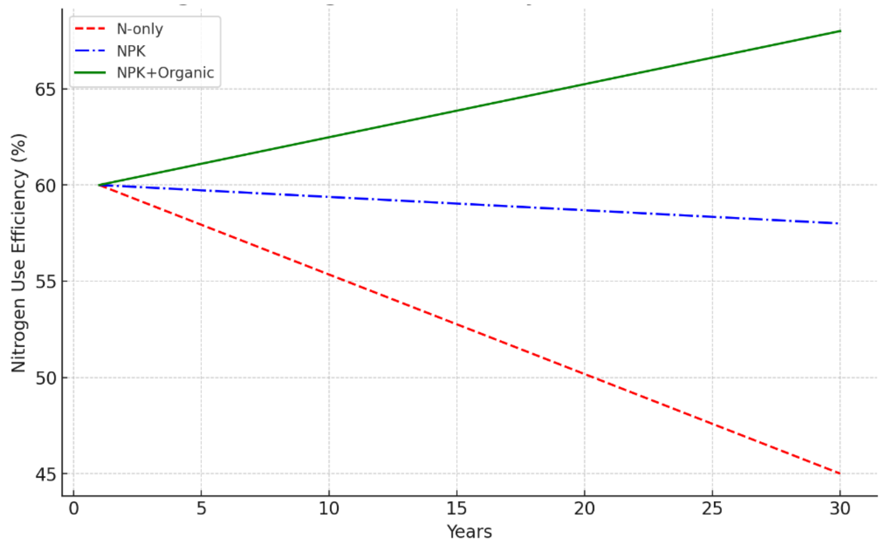

Figure 3:Nitrogen Use Efficiency Trend Over 30 Years

Table 6 compares the average yield and nitrogen uptake efficiency in relation to regime, in terms of crop productivity. NPK+Organic has produced the highest yield (4.6 t/ha) and NUE (68 per cent). N-only is poor in terms of performance (3.5 t/ha yield), moreover, endangering long-term deterioration.

Table 6. Crop Yield and Nitrogen Uptake Efficiency

Treatment	Crop Yield (t/ha)	N Uptake Efficiency (%)
NPK	4.2	60
N-only	3.5	50
NPK+Organic	4.6	68

4.3 Fertilizer Usage Trends and Contextual Validation

Macroscopic examination with the use of FAOSTAT databank (19902020) reveals that there is an imbalanced growth in the consumption of nitrogen fertilizers in the world as well as stagnation in terms of phosphorus and potassium consumption. This unbalance leads to long term depletion of nutrients, degrading NUE, and greenhouse gas emissions which are trends reflected in the output of the model. It is against this trend that the simulation baseline assumptions are checked. In order to give the simulation scenarios some international context, Figure 4 shows long-term trends in NPK fertilizer use relying on aggregated data of the FAOSTAT kind (1990-2020). It identifies an increasing application of nitrogen globally, which has certain food concern regarding nutrient loading of the environment and efficiencies

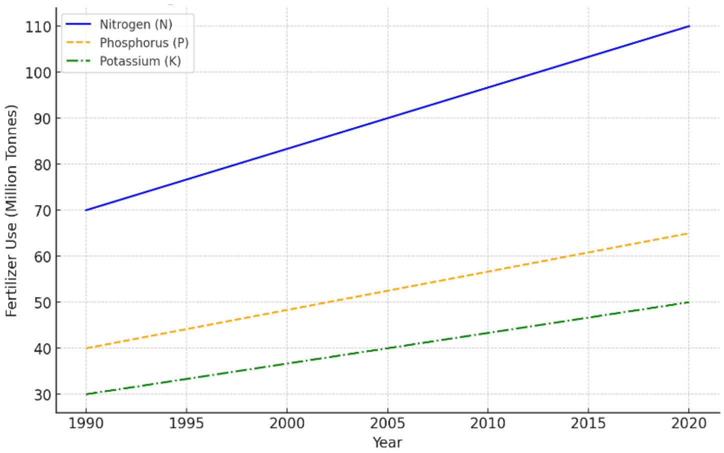

Figure 4:Global Fertilizer Use Trends (1990–2020)

The trends support the necessity to change to more sustainable and levelled nutrient management models, especially in the densely farmed areas.

5. Policy Implications and Strategic Implementation

The result of this conceptual simulation gives a practical approach in the redefinition of nutrient control policy according to the principle of sustainability and environmental protection. The research makes it clear than to have effective long-term soil fertility and crop productivity, it is important to develop the alternative model of implementing integrated and ecologically balanced systems, rather than conventional and demanding large-input. Remarkably, integrating mineral fertilizers and organic sources of nutrients, including compost, crop residues, or green manures, namely, Implemented Nutrient Management (INM) was shown to prevail over singular mineral-based systems in terms of soil organic carbon (SOC) maintenance, maximal nutrient use efficiency (NUE), and stable soil pH maintenance.

5.1 Rethinking Fertilizer Subsidy Policies

Most existing subsidy programs in most developing countries favor urea and other nitrogen-based fertilizers, which, by default, boost overuse and imbalance of nutrients. There must be a strategic change which will see organic inputs such as farm yard manure, compost and biochar formally integrated in subsidy programmes. This would encourage the practice of balanced fertilizing and nutrient loop-closure at farm level. Moreover, the use of the incentives to engender residue recycling and crop diversification could be set into translations with the INM principles.

5.2 Strengthening Soil Testing and Nutrient Budgeting Infrastructure

Although more people are getting aware of the need to test the soil, routine soil testing is not easily available especially in the smallholder-predominant systems. The regional authorities and Agricultural extension entities should focus on establishment of strong soil laboratories and portable diagnostic facilities. Enforcing regular soil health evaluation using digitalized soil health cards have the potential to harmonise the approach to nutrient budgeting and give feedback on fertilizer recommendation across sites. Such actions, combined with farmer education and advisory tools can eliminate nutrient losses and inefficiencies by a huge margin.

5.3 Leveraging Digital Tools and AI in Nutrient Management

The development of precision agriculture brings unknown opportunities in the precision of nutrient applications. Prediction in real-time of nutrient deficiencies can be achieved by AI-powered systems, remote sensing, and geospatial applications and can optimize the application timing, location, and rates of fertilizers. The adoption of this digital infrastructure in extension services particularly in the data-rich areas is likely to facilitate closure of the knowledge-gap between scientific recommendations and practice in fields.

5.4 Climate-Aligned Nutrient Governance

The policy-relevant environmental impacts of nutrient overuse, amongst them nitrate leaching, eutrophication and nitrous oxide (N 2 O) emission are mounting. Nutrient losses as an agronomic waste should not be considered as part of regulatory frameworks but also taken as a pollutant. It is important that nitrogen efficiency objectives be integrated in climate smart plans of countries as countries update their nationally determined contributions (NDCs) within the framework of the Paris accord. Interregional collaboration among ministries of agriculture and environment is the major issue in the establishment of integrated nutrient governance structures that resonate food security with ecological integrity.

5.5 Climate-Aligned Nutrient Governance

None of the policy frameworks can work without the involvement and awareness of a farmer. Various literacy levels training programs are essential, including field demonstration training, mobile-based micro-learning, and so on. The universities and agricultural colleges also ought to incorporate INM, soil biology, and modeling in sustainability to create future generation of agro-environmental professionals.

Discussion

Future simulation modeling results indicate that the nutrient flow and soil quality about significantly change with different fertilization approaches. The increase in nitrogen acidification and decreasing soil organic carbon (SOC) in nitrogen-only (N-only) fertilization fits well into known biochemical processes. Unbalanced nitrogen (lack of phosphorus or potassium) will increase nitrification processes, producing hydrogen ions and causing a decline in pH of the soil. Lack of organic amendments divert microbial activity and carbon replenishment leading to poor soil structure and raising the rate of nutrient losses. On the contrary, integrated NPK+Organic encourages a more robust nutrient cycle. The presence of organic matter does not only support the occurrence of SOC but it also mitigates acidification by means of increased cation exchange and microbial immobilization. Such conditions invoke biomass and enzyme action of microbes and promote the better availability of phosphorus and retention of nutrients in the long-term. Such modelled dynamics are very similar to long term trial results like those of Rothamsted and ICRISAT. Such studies indicate that persistent application of Integrated Nutrient Management (INM) sustains the yields and enhances the quality of soil through decades. The current study shows that the efficiency of nitrogen use and reduced nutrient losses in compost-based and legume-based systems, as stated in the research by Hazra et al. (2014) and Mandal et al. (2007), is confirmed by the results of the current study. Though a simulation-based model, it is calibrated against peer-reviewed field measurements, trend data in FAOSTAT and meta-analytic standards, which gives it a high level of external validity. Although local soil-climate interactions are not clear resolved, the framework is solid in terms of global-scale interpretations of nutrient sustainability. Regarding the environmental effects, the production of incomplete nitrogen recovery in the case of N-only regimes is alarming. Over application of nitrogen can become a major cause of nitrate leaching, ground water pollution, and subsequent rise in nitrous oxide (N 2 O) emissions that are green house gases with a high global warming capacity. These are some of the examples of overall ecological impacts of mismanagement of nutrients and they demonstrate the connections between bad farming practices and climatic alteration and ecosystem deterioration.

This study is also worthwhile since it is conceptually effective with well-established data with backing. The quantities of fertilizer applied, uptake coefficients, and the loss factors in nutrients have been taken off reputable sources including FAO and the peer review literature. However, no local rain patterns, different genotype uptake capacities, and micro-bial diversity is an aspect of the limitation. In subsequent versions such issues can be improved by incorporating process-based models like APSIM or DNDC to enhance regional correspondence. In general the results have a strong case which promotes Integrated Nutrient Management as a solution to sustainable farming. INM combines the immediate product-enhancing properties of mineral fertilizer with the long-run nutrient building and soil structural properties of organic materials. In order to facilitate this change, one should promote localized nutrient planning, implement subsidizing of organic amendments, and subsidizing monitoring tools. In addition, there exists opportunities in precision agriculture to ensure efficient nutrient utilization, environmental friendliness, and development of resilient and climate smart agroecosystems.

Conclusion

This paper points out the importance of fertilizer management to realize soil plant nutrient processes and environmental sustainability. The simulations on the 30-year period using nitrogen-only (N-only) applications resulted in a decrease in soil organic carbon (SOC) and acidity of soils, as well as a decrease of nitrogen use efficiency (NUE). Long term debasing, even at an early stage of increase in production, is suggested by such consequences of unbalanced nutrient input. By contrast, there were obvious advantages of integrated nutrient management (NPK+Organic). It either kept or raised the level of SOC, adjusted the soil pH, increased NUE and limited nitrogen losses via leaching and volatilization. These trends are in line with the results of the long-term field experiments around the world and they prove that organic amendments stabilize soil health and yields. Although the proposed work is not purely an experimental one, the results are based on powerful datasets and field research findings. Findings emphasize the environmental hazards of excess nutrient supply such as water pollution and emission of green house gases, and they powerfully argue in support of localized, balanced fertilization approaches. To bring it to a close, sustainable agriculture involves the need to move away with the input-intensive system to integrated systems where the best of both yield and the environmental results is ensured. To create responsive and 4nitrogen-efficient agroecosystems, policymakers need to advertise INM practices and precision technologies.

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