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Impact of Balanced Use of Fertilizer on Crop Production and Its Quality for Human Health

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Abstract

Balanced fertilizer use represents a comprehensive approach to plant nutrition that extends beyond the routine application of nitrogen (N), phosphorus (P), and potassium (K). It involves the judicious supply of essential macro- and micronutrient including sulfur, zinc, iron, and boron, based on crop requirements, soil nutrient status, and prevailing agro-ecological conditions. Evidence from long-term field experiments and multi-location studies conducted across Asia, Europe, and developing agrarian economies consistently demonstrates that balanced nutrient management plays a pivotal role in enhancing crop productivity, nutrient use efficiency, and produce quality.

Global research findings indicate that balanced fertilization significantly increases biomass accumulation, grain yield, and nutrient uptake while improving critical quality parameters such as protein content, grain density, oil composition, and micronutrient concentration. In addition to yield and quality improvements, balanced fertilizer practices contribute to improved soil health by enhancing soil organic matter, strengthening nutrient cycling processes, and stimulating beneficial microbial activity. These effects collectively support the sustainability and resilience of intensive cropping systems.

In contrast, imbalanced fertilizer uses, commonly characterized by excessive nitrogen application and the omission of phosphorus, potassium, sulfur, and micronutrients has been associated with soil nutrient depletion, structural degradation, declining factor productivity, and inferior crop quality over time. Such practices not only reduce long-term yield stability but also increase environmental risks and compromise food system sustainability.

This review synthesizes global research evidence on the effects of balanced fertilizer use on crop production and quality. It underscores balanced nutrient management as a fundamental strategy for sustainable agricultural intensification, improved farm profitability, and long-term food and nutritional security under increasing population pressure and climatic variability.

Keywords: *Balanced fertilization; Nutrient management; Crop yield; Crop quality; Soil health; Human health; Sustainable agriculture.*

INTRODUCTION

Fertilizers play a central role in modern agriculture by supplying essential nutrients required for optimal crop growth and productivity. Among these, nitrogen (N), phosphorus (P), and potassium (K) are the primary macronutrients, while secondary and micronutrients such as sulfur (S), zinc (Zn), iron (Fe), and boron (B) are equally critical for metabolic processes, enzyme activation, and crop quality formation. However, crop productivity and quality are not determined solely by fertilizer quantity but by the *balance* and *proportional availability* of nutrients in relation to soil status and crop demand (Magen, 2008).

Globally, intensive agricultural practices have led to widespread nutrient imbalances, particularly excessive nitrogen application combined with insufficient phosphorus, potassium, and micronutrients. Studies conducted in Asia, Europe, and Africa indicate that such imbalanced fertilizer use initially increases yields but eventually results in declining soil fertility, reduced nutrient use efficiency, and deterioration of crop quality parameters (Krasilnikov *et al.*, 2022). Long-term experiments have demonstrated that continuous nitrogen-dominant fertilization accelerates soil acidification, depletes potassium reserves, and disrupts soil microbial activity, thereby threatening sustainable crop production systems (Zhang *et al.*, 2025).

Balanced fertilizer use, defined as the application of nutrients in appropriate ratios based on soil testing and crop requirements, has been shown to significantly improve crop productivity and resource efficiency. Global research findings report that balanced fertilization enhances biomass accumulation, grain yield, and nutrient uptake in cereals, legumes, and horticultural crops (Sharma, 2009). In wheat–maize cropping systems, balanced NPK application combined with secondary and micronutrients has resulted in sustained yield improvements and increased soil organic carbon sequestration, indicating long-term soil health benefits (Zhang *et al.*, 2025).

Beyond yield enhancement, balanced nutrient management plays a crucial role in improving crop quality. Studies across different agro-ecological zones reveal that balanced fertilization increases protein content, grain weight, nutrient density, and overall produce quality compared to unbalanced fertilization regimes (Trivedi *et al.*, 2020). Potassium and sulfur, in particular, have been associated with improved grain filling, enhanced stress tolerance, and better shelf life in food crops, highlighting the quality-driven importance of nutrient balance (IPI, 2025).

In developing countries such as Pakistan, India, and China, declining soil fertility and nutrient mining have emerged as major constraints to agricultural sustainability. Research conducted under South Asian conditions shows that integrating macro- and micronutrients through balanced fertilizer strategies significantly improves crop performance and reduces yield variability under resource-limited farming systems (Yousaf *et al.*, 2020). These findings emphasize the need for evidence-based fertilizer management approaches to ensure food security while preserving soil resources.

Given the growing pressure to increase agricultural output while minimizing environmental degradation, balanced fertilizer use has gained global recognition as a key strategy for sustainable intensification. This study reviews and synthesizes worldwide research on balanced fertilization, focusing on its impact on crop production, quality attributes, and soil health, thereby contributing to informed nutrient management policies and practices.

Objectives of the Study

The objectives of this study are:

- To review global research findings on the impact of balanced fertilizer use on crop production across different agro-ecological regions.
- To assess the effect of balanced fertilization on crop quality parameters, including protein content, nutrient density, and yield attributes.
- To examine the role of balanced nutrient management in improving soil health and sustainability, based on long-term experimental evidence.
- To compare balanced and imbalanced fertilizer practices and their implications for crop productivity and soil fertility.
- To highlight the importance of balanced fertilizer use for sustainable agriculture and food security at both regional and global levels.

MATERIALS AND METHODS

Study Design

This study adopted a systematic review and comparative synthesis approach to evaluate the effects of balanced fertilizer use on crop yield, crop quality, soil health, and sustainability outcomes. The methodology was designed to integrate findings from long-term field experiments, multi-location trials, and institutional studies conducted under diverse agro-ecological conditions worldwide (FAO, 2019; Krasilnikov *et al.*, 2022).

Data Sources

Scientific literature was retrieved from internationally recognized databases, including Web of Science, Scopus, ScienceDirect, and Google Scholar, alongside reports from authoritative organizations such as the Food and Agriculture Organization (FAO) and the International Potash Institute (IPI). Studies published between 2000 and 2025 were prioritized to ensure relevance to contemporary fertilizer management practices and sustainability goals (Magen, 2008; IPI, 2025).

Selection Criteria

Studies were selected based on the following inclusion criteria:

- Field-based or long-term experiments comparing balanced and imbalanced fertilizer practices
- Focus on major crops including wheat, maize, rice, sugarcane, potato, cotton, and legumes
- Quantitative reporting of yield, crop quality parameters, and soil health indicators
- Conducted under contrasting soil and climatic conditions across Asia, Africa, Europe, and South America

Studies lacking quantitative fertilizer comparisons or clear methodological descriptions were excluded to maintain analytical rigor (Bhattacharyya *et al.*, 2019; Zhang *et al.*, 2025).

Classification of Fertilizer Practices

Fertilizer regimes were categorized into:

- Imbalanced fertilization, characterized by nitrogen-dominant or single-nutrient application, commonly observed in conventional farmer practices
- Balanced fertilization, involving the application of nitrogen, phosphorus, and potassium in recommended ratios, often supplemented with sulfur, zinc, or boron based on soil testing or integrated nutrient management strategies (Sharma, 2009; Krasilnikov *et al.*, 2022)

Data Extraction and Synthesis

From each selected study, data were extracted on crop type, region, fertilizer treatments, yield response, quality attributes, and soil health indicators such as soil organic carbon, nutrient availability, pH, and microbial activity (Trivedi *et al.*, 2020; Yousaf *et al.*, 2020). The extracted data were synthesized using comparative and thematic analysis, allowing cross-crop and cross-regional evaluation of balanced versus imbalanced fertilizer effects. Summary tables were developed to present yield, quality, and soil health responses in a structured manner (FAO, 2019).

Linkage to Sustainability and Food Security

The findings were interpreted in the context of sustainable agricultural intensification, food security dimensions, and the United Nations Sustainable Development Goals (SDGs), particularly SDGs 2, 12, 13, and 15 (FAO, 2019; IPI, 2025). This integrative framework ensured that agronomic outcomes were evaluated alongside environmental and socio-economic implications

RESULTS AND DISCUSSION

Effect of Balanced Fertilizer Use on Crop Yield

Results from global field experiments consistently demonstrate that balanced fertilizer application significantly increases crop yields compared to imbalanced or nutrient-deficient fertilization practices. In long-term wheat–maize cropping system trials conducted in China, balanced application of NPK combined with sulfur and zinc increased grain yield by 18–32% compared to nitrogen-only treatments (Zhang *et al.*, 2025). These yield gains were attributed to improved nutrient uptake efficiency, enhanced root development, and increased soil organic carbon, which collectively supported sustained crop growth over successive seasons.

Similarly, multi-location experiments conducted across the Indo-Gangetic Plains of India revealed that balanced NPK fertilization increased wheat (*Triticum aestivum* L.) grain yield from 4.2 t ha^{-1} under nitrogen-only fertilization to 5.6 t ha^{-1}, representing a 33% yield improvement (Trivedi *et al.*, 2020). The addition of sulfur and zinc further improved spike density, grain number per spike, and thousand-grain weight, confirming the synergistic effects of balanced macro- and micronutrient supply.

In maize (*Zea mays* L.) production systems, coordinated trials across sub-Saharan Africa and South Asia reported yield increases ranging from 20–40% under balanced fertilization compared to prevailing farmer practices dominated by nitrogen application alone (FAO, 2019). Balanced NPK application improved phosphorus availability and potassium-mediated water regulation, resulting in better cob formation, higher kernel number, and improved harvest index.

Rice (*Oryza sativa* L.) also showed strong yield responses to balanced fertilizer management. Long-term experiments in China and Southeast Asia demonstrated that integrating NPK with zinc and sulfur increased paddy yields by 15–28% relative to nitrogen-dominant fertilization systems (Magen, 2008). Yield improvements were linked to enhanced tillering, improved panicle fertility, and reduced spikelet sterility under balanced nutrient regimes.

In sugarcane (*Saccharum officinarum* L.), studies conducted in Brazil and India reported that balanced fertilization increased cane yield by 20–30% compared to imbalanced fertilizer use, particularly when potassium was adequately supplied alongside nitrogen and phosphorus (IPI, 2025). Adequate potassium nutrition improved stalk elongation, juice quality, and sucrose accumulation, directly contributing to higher sugar recovery per hectare.

Potato (*Solanum tuberosum* L.) trials across Europe and South Asia revealed that balanced NPK fertilization resulted in tuber yield increases of 18–35% compared to nitrogen-heavy fertilization practices (*Krasilnikov, 2022*). Potassium-balanced treatments enhanced tuber size uniformity, dry matter content, and resistance to physiological disorders, demonstrating the importance of nutrient balance in tuber crops.

Cotton (*Gossypium hirsutum* L.) production also benefited significantly from balanced fertilizer use. Field experiments in Pakistan and India showed that balanced NPK combined with boron and zinc increased seed cotton yield by 25–40% compared to nitrogen-only treatments (Yousaf *et al.*, 2020). Improved boll retention, fiber development, and nutrient translocation were identified as key contributors to higher productivity under balanced nutrient management.

Collectively, these global findings confirm that balanced fertilizer use consistently enhances crop yield across cereals, cash crops, and tuber crops. Yield gains observed across diverse agro-ecological regions highlight the universal relevance of balanced nutrient management as a scientifically proven strategy for improving crop productivity and agricultural sustainability. Results are summarized in Table 1.

Impact on Crop Quality Parameters

Beyond yield enhancement, balanced fertilizer use has been consistently shown to improve a wide range of crop quality attributes, including protein content, nutrient density, fiber quality, sugar accumulation, and storage characteristics. These improvements arise from optimized nutrient uptake, improved physiological efficiency, and enhanced metabolic processes under balanced nutrient supply.

Wheat (Triticum aestivum L.)

In wheat, balanced fertilization has a pronounced effect on grain quality, particularly protein content and grain weight. Field experiments conducted across India demonstrated that grain protein content increased from 10.8% under

Table 1: Effect of balanced fertilizer use on crop yield across major crops.

Crop	Region / Study Area	Fertilizer Treatments Compared	Yield Under Imbalanced / N-only Fertilization	Yield Under Balanced Fertilization	Yield Increase (%)	Key Observations	References of the Study
Wheat (*Triticum aestivum* L.)	China (wheat–maize cropping system)	N-only vs. NPK + S + Zn	N-only baseline	Significantly higher grain yield	18–32%	Improved nutrient uptake, root growth, soil organic carbon	Zhang, *et al*. (2025)
Wheat (*Triticum aestivum* L.)	India (Indo-Gangetic Plains)	N-only vs. balanced NPK + S, Zn	4.2 t ha^{-1}	5.6 t ha^{-1}	33%	Increased tillers, grain weight, spike density	Trivedi, *et al*. (2020)
Maize (*Zea mays* L.)	Sub-Saharan Africa & South Asia	Farmer practice (N-dominant) vs. balanced NPK	Lower, variable yields	Higher and stable yields	20–40%	Improved cob formation, kernel number, harvest index	FAO (2019).
Rice (*Oryza sativa* L.)	China & Southeast Asia	N-dominant vs. NPK + S + Zn	Lower paddy yield	Higher paddy yield	15–28%	Enhanced tillering, panicle fertility, reduced spikelet sterility	Magen (2008).
Sugarcane (*Saccharum officinarum* L.)	Brazil & India	Imbalanced fertilization vs. balanced NPK (adequate K)	Reduced cane yield	Increased cane yield	20–30%	Improved stalk elongation, juice quality, sucrose accumulation	IPI (2025).
Potato (*Solanum tuberosum* L.)	Europe & South Asia	N-heavy vs. balanced NPK	Lower tuber yield	Higher tuber yield	18–35%	Improved tuber size uniformity, dry matter content	Krasilnikov *et al*. (2022)
Cotton (*Gossypium hirsutum* L.)	Pakistan & India	N-only vs. balanced NPK + B + Zn	Lower seed cotton yield	Higher seed cotton yield	25–40%	Better boll retention, fiber development	Yousaf *et al*. (2020)

imbalanced fertilization to 13.2% when NPK application was supplemented with sulfur and zinc (Trivedi *et al.*, 2020). Sulfur played a critical role in amino acid synthesis, while zinc enhanced nitrogen metabolism, resulting in improved grain protein composition and baking quality. Additional studies reported increases in thousand-grain weight by 8–15% under balanced nutrient regimes, indicating superior grain filling and end-use quality (Magen, 2008).

Maize (Zea mays L.)

Balanced fertilization has also been linked to improvements in maize grain quality. Multi-location trials in Africa and South Asia revealed that balanced NPK fertilization increased grain protein concentration by 10–18% compared to nitrogen-dominant fertilization (FAO, 2019). Adequate potassium supplies improved carbohydrate translocation, while phosphorus enhanced kernel development, resulting in higher test weight and improved grain density. These quality improvements are particularly important for maize used in both human consumption and animal feed.

Rice (Oryza sativa L.)

In rice, balanced nutrient management significantly improves both yield quality and nutritional value. Long-term field experiments in Southeast Asia reported that balanced fertilization increased grain zinc concentration by 25–40%, directly enhancing micronutrient density and contributing to efforts aimed at reducing zinc deficiency in human diets (Magen, 2008). Balanced NPK combined with sulfur also improved milling recovery and reduced grain chalkiness, leading to better market value and consumer acceptability (Krasilnikov *et al.*, 2022).

Sugarcane (Saccharum officinarum L.)

Sugarcane quality is strongly influenced by potassium nutrition. Studies conducted in Brazil and India demonstrated that balanced fertilization increased sucrose content by 12–20% and improved juice purity compared to imbalanced fertilizer practices (IPI, 2025). Potassium-balanced treatments enhanced photosynthate transport and enzymatic activity, resulting in higher commercial cane sugar yield per hectare. These improvements directly translate into increased profitability for the sugar industry.

Potato (Solanum tuberosum L.)

In potato, balanced fertilizer application significantly improves tuber quality attributes. Experiments conducted in Europe and South Asia showed that balanced NPK fertilization increased tuber dry matter content by 10–18% and reduced the incidence of physiological disorders such as hollow heart and bruising (Krasilnikov *et al.*, 2022). Adequate potassium nutrition improved starch accumulation and tuber firmness, leading to better processing quality and longer storage life.

Cotton (Gossypium hirsutum L.)

Cotton quality parameters, particularly fiber length and strength, are highly responsive to balanced nutrient supply. Field trials in Pakistan and India revealed that balanced NPK fertilization supplemented with boron and zinc improved

Table 2: Effect of balanced fertilizer use on crop quality parameters across major crops.

Crop	Quality Parameter Assessed	Quality Under Imbalanced / N-dominant Fertilization	Quality Under Balanced Fertilization	Improvement Range	Key Quality Improvements Observed	References
Wheat (*Triticum aestivum* L.)	Grain protein content (%)	10.8%	13.2%	↑ ~22%	Enhanced protein synthesis due to improved N and S assimilation; better baking quality	Trivedi *et al.* (2020); Magen (2008)
Maize (*Zea mays* L.)	Grain protein content & test weight	Lower protein concentration	Higher protein concentration	↑ 10–18%	Improved kernel density and grain nutritional value	FAO (2019)
Rice (*Oryza sativa* L.)	Grain zinc concentration (mg kg^{-1})	Low Zn concentration	Increased Zn concentration	↑ 25–40%	Improved micronutrient density; reduced grain chalkiness; better milling quality	Magen (2008); Krasilnikov *et al.* (2022)
Sugarcane (*Saccharum officinarum* L.)	Sucrose content (%) & juice purity	Lower sucrose accumulation	Higher sucrose content	↑ 12–20%	Improved sugar recovery and juice quality due to adequate K nutrition	IPI (2025)
Potato (*Solanum tuberosum* L.)	Tuber dry matter content (%)	Lower dry matter	Higher dry matter	↑ 10–18%	Improved starch accumulation, firmness, and storage quality	Krasilnikov *et al.* (2022)
Cotton (*Gossypium hirsutum* L.)	Fiber length & strength	Shorter, weaker fibers	Longer and stronger fibers	↑ 8–15%	Improved boll retention, fiber maturity, and lint quality	Yousaf *et al.* (2020)

fiber length by 8–12% and fiber strength by 10–15% compared to nitrogen-only treatments (Yousaf *et al.*, 2020). Improved boll retention and enhanced nutrient translocation under balanced fertilization contributed to superior lint quality and higher market value.

Synthesis of Quality Responses

Across cereals, cash crops, and tuber crops, balanced fertilizer use consistently enhanced crop quality by:

- Increasing protein and nutrient density (wheat, maize, rice);
- Improving sugar and starch accumulation (sugarcane, potato);
- Enhancing fiber quality and marketability (cotton); and
- Reducing post-harvest losses and storage disorders.

These findings strongly support the role of balanced fertilizer management not only in increasing crop yields but also in improving the nutritional and commercial quality of agricultural produce worldwide. Results are summarized in Table 2.

Balanced Fertilization and Soil Health Sustainability

Long-term experimental evidence from diverse agro-ecological regions confirms that balanced fertilizer use plays a critical role in maintaining and improving soil health, which is fundamental for sustainable crop production. In a 20-year field experiment in northern China, balanced fertilization significantly increased soil organic carbon (SOC) by 0.3–0.5%, whereas nitrogen-only treatments resulted in progressive soil acidification, depletion of base cations, and a decline in microbial biomass carbon (Zhang et al., 2025). Enhanced SOC under balanced fertilization improved soil structure, water-holding capacity, and nutrient retention, thereby supporting sustained crop productivity.

Similar findings have been reported from long-term fertilizer experiments in India. A 25-year study under rice–wheat cropping systems revealed that balanced NPK fertilization increased SOC by 20–35% compared to nitrogen-only plots and significantly improved soil aggregate stability and available phosphorus levels (Bhattacharyya *et al.*, 2019). These improvements were directly linked to higher nutrient use efficiency and reduced nutrient losses, highlighting the sustainability benefits of balanced nutrient management.

In Europe, long-term trials conducted under temperate cropping systems demonstrated that balanced fertilization enhanced soil biological activity. Microbial biomass carbon increased by 15–28%, and soil enzyme activities related to nitrogen and phosphorus cycling were significantly higher in balanced NPK treatments compared to imbalanced fertilization regimes (Krasilnikov *et al.*, 2022). These biological improvements promoted more efficient nutrient cycling and reduced dependency on excessive fertilizer inputs.

Krasilnikov *et al.* (2022) further reported that excessive nitrogen application without adequate phosphorus and potassium accelerated potassium depletion, reduced soil pH by 0.4–0.8 units, and impaired nutrient availability, ultimately affecting crop performance. In contrast, balanced nutrient management maintained soil pH within optimal ranges and improved exchangeable potassium and available phosphorus status, thereby sustaining soil fertility over time.

Table 3: Effect of balanced fertilizer use on soil health indicators across different regions.

Region / Country	Cropping System	Fertilizer Practice Compared	Key Soil Health Indicators Measured	Soil Health Response Under Balanced Fertilization	Soil Degradation Under Imbalanced Fertilization	References
China	Wheat–maize rotation	N-only vs. balanced NPK (+ S, Zn)	Soil organic carbon (SOC), microbial biomass, soil pH	SOC increased by 0.3–0.5%; higher microbial biomass; stable soil pH	Soil acidification; decline in microbial biomass	Zhang *et al.* (2025)
India	Rice–wheat system	N-only vs. balanced NPK	SOC, aggregate stability, available P	SOC increased by 20–35%; improved soil aggregation and P availability	Nutrient imbalance; reduced soil structure	Bhattacharyya *et al.* (2019)
Europe	Temperate cereal systems	Imbalanced vs. balanced NPK	Microbial biomass C, soil enzyme activity	Microbial biomass increased by 15–28%; enhanced enzyme activity	Reduced biological activity	Krasilnikov *et al.* (2022)
Sub-Saharan Africa	Maize-based systems	Farmer practice (N-dominant) vs. balanced NPK	Soil N stocks, nutrient balance	Soil N stocks increased by 18–30%; reduced nutrient mining	Nutrient depletion; yield instability	FAO (2019)
Pakistan	Mixed cropping systems	Conventional vs. balanced macro + micronutrients	Available P, exchangeable K	Available P increased by 12–25%; K increased by 10–20%	Declining soil fertility indicators	Yousaf *et al.* (2020)
Global synthesis	Multiple cropping systems	Imbalanced vs. balanced fertilization	SOC, pH, nutrient cycling, microbial diversity	Improved nutrient cycling, soil resilience, long-term fertility	Acidification, K depletion, biological decline	Krasilnikov *et al.* (2022)

Evidence from sub-Saharan Africa supports similar conclusions. Long-term maize-based experiments showed that balanced fertilization increased soil nitrogen stocks by 18–30% and reduced nutrient mining compared to farmer practices dominated by nitrogen application alone (FAO, 2019). Improved soil fertility under balanced nutrient regimes resulted in more stable yields and reduced inter-seasonal variability, particularly under rainfed conditions.

In Pakistan, field trials integrating macro- and micronutrients such as sulfur and zinc demonstrated significant improvements in soil fertility indicators. Available phosphorus increased by 12–25%, and exchangeable potassium by 10–20%, compared to imbalanced fertilization practices (Yousaf *et al.*, 2020). These improvements translated into stable yield gains across multiple seasons and reduced yield fluctuations under resource-limited farming systems.

Collectively, global research evidence clearly indicates that balanced fertilizer use enhances soil chemical, physical, and biological properties, thereby promoting long-term agricultural sustainability (Table 3). By preventing soil acidification, reducing nutrient depletion, and enhancing microbial activity, balanced nutrient management supports resilient cropping systems capable of sustaining productivity while minimizing environmental degradation.

Comparison of Balanced and Imbalanced Fertilizer Practices

Comparative analyses from long-term and multi-location studies worldwide clearly indicate that imbalanced fertilizer practices, particularly nitrogen-dominant regimes, may provide short-term yield gains but ultimately result in declining productivity, reduced crop quality, and soil degradation. In contrast, balanced fertilization consistently outperforms imbalanced nutrient application in terms of yield stability, quality parameters, nutrient use efficiency, and soil fertility across diverse cropping systems (Sharma, 2009; Krasilnikov *et al.*, 2022).

Long-term experiments in China comparing nitrogen-only fertilization with balanced NPK application in cereal systems revealed that nitrogen-dominant treatments initially increased yields but caused a 15–25% yield decline after 10–15 years, primarily due to soil acidification and potassium depletion. Balanced fertilization maintained stable yields over time and improved soil organic carbon and nutrient availability (Zhang *et al.*, 2025). These findings demonstrate that yield sustainability is strongly dependent on nutrient balance rather than nutrient quantity alone.

In South Asia, comparative trials under rice–wheat systems showed that nitrogen-only fertilization resulted in declining phosphorus and potassium availability, leading to reduced grain yield and quality. Balanced NPK fertilization, however, increased system productivity by 20–30% and improved grain protein content and milling quality compared to imbalanced practices (Bhattacharyya *et al.*, 2019). These results emphasize the role of balanced fertilization in sustaining intensive cropping systems.

Legume crops provide a particularly clear contrast between balanced and imbalanced fertilizer use. Studies on chickpea and lentil reported yield increases of 25–35% under balanced fertilization compared to unfertilized or nitrogen-only treatments, alongside enhanced biological nitrogen fixation and improved soil nitrogen status (Sharma, 2009). Excessive nitrogen application in legumes suppressed nodulation and nitrogen fixation, highlighting the inefficiency and counterproductive nature of imbalanced nutrient management in these systems.

In maize-based systems across sub-Saharan Africa, farmer practices dominated by nitrogen application led to nutrient mining and yield instability. Balanced NPK fertilization increased maize yields by 20–40% and reduced inter-annual yield variability compared to imbalanced fertilizer use (FAO, 2019). Improved nutrient balance enhanced phosphorus uptake and potassium-mediated water regulation, contributing to greater resilience under variable climatic conditions.

Similarly, cotton production systems in Pakistan and India showed that nitrogen-dominant fertilization increased vegetative growth but reduced boll retention and fiber quality. Balanced NPK fertilization supplemented with boron and zinc increased seed cotton yield by 25–40% and improved fiber length and strength compared to imbalanced nutrient regimes (Yousaf *et al.*, 2020). These findings demonstrate that balanced fertilization improves both yield and market quality, whereas imbalanced fertilization compromises economic returns.

Overall, global evidence clearly demonstrates that balanced fertilization provides superior long-term outcomes compared to imbalanced nutrient management. While nitrogen-dominant fertilization may appear economically attractive in the short term, it leads to declining soil fertility, reduced nutrient use efficiency, and lower crop quality over time. Balanced fertilizer practices, supported by soil testing and integrated nutrient management, offer a sustainable pathway to maintaining productivity, improving crop quality, and preserving soil health.

Impact of Imbalanced Use of Fertilizers on Human Health

Balanced fertilizer application positively influences human health by enhancing the nutritional quality of agricultural produce through optimized accumulation of essential macro- and micronutrients. Adequate and proportionate nitrogen supply promotes efficient amino acid synthesis and protein formation in cereals and legumes, improving dietary protein quality and supporting muscle development, immune function, and metabolic health in humans (Trivedi *et al.*, 2020; Fixen *et al.*, 2015). Balanced phosphorus nutrition enhances energy metabolism in plants, resulting in improved grain development and higher concentrations of bioavailable phosphorus in food crops, which is essential for bone formation and cellular energy transfer in humans (Magen, 2008). Proper potassium fertilization improves carbohydrate metabolism, sugar translocation, and starch synthesis, leading to higher-quality grains, tubers, and fruits with improved energy density and cardiovascular health benefits due to potassium's role in blood pressure regulation (IPI, 2025). Moreover, balanced inclusion of micronutrients such as iron and zinc significantly increase their concentration in edible plant parts, directly addressing micronutrient deficiencies, anemia, impaired immunity, and cognitive development challenges prevalent in cereal-based diets (Magen, 2008; FAO, 2019). Boron supplementation enhances cell wall integrity, reproductive development, and nutrient translocation in crops, indirectly improving mineral bioavailability and overall produce quality for human consumption (Yousaf *et al.*, 2020). Collectively, balanced fertilization strengthens the soil–plant–human nutrient continuum by improving amino acid profiles, mineral density, and physiological quality of food crops, thereby contributing to improved nutritional security, disease resistance, and long-term human health outcomes.

Adverse Impact of Imbalanced Use of Fertilizers on Human Health

While balanced fertilizer use enhances crop quality and supports human nutrition, imbalanced fertilizer practices—particularly nitrogen-dominant and single-nutrient applications—pose significant risks to human health, both directly and indirectly. Excessive nitrogen use combined with inadequate phosphorus, potassium, sulfur, and micronutrients disrupts soil–plant–human nutrient linkages, resulting in poor food quality, environmental contamination, and long-term public health concerns.

One of the most documented adverse effects of imbalanced fertilization is excess nitrate accumulation in food crops and water resources. High nitrogen application increases nitrate concentration in leafy vegetables and cereals, which, upon ingestion, can be converted to nitrites in the human body. This process interferes with oxygen transport in blood, leading to conditions such as *methemoglobinemia*, particularly in infants and vulnerable populations (Fixen *et al.*, 2015; FAO, 2019).

Imbalanced fertilization also contributes to micronutrient dilution in staple foods. Continuous nitrogen-heavy fertilization increases biomass but reduces the concentration of essential micronutrients such as zinc, iron, and selenium in grains. This phenomenon exacerbates "*hidden hunger*," a form of malnutrition that affects billions globally, especially in developing countries where diets are cereal-based (Magen, 2008; FAO, 2019).

In addition, excessive and unregulated fertilizer use can increase the uptake of toxic heavy metals, such as cadmium and lead, from contaminated phosphate fertilizers. These toxic elements enter the food chain through crops and accumulate in human tissues, increasing the risk of kidney dysfunction, bone demineralization, and carcinogenic effects over long-term exposure (Krasilnikov *et al.*, 2022).

Water contamination represents another critical pathway through which imbalanced fertilizer use affects human health. Nitrogen leaching into groundwater and surface water bodies leads to unsafe drinking water, contributing to gastrointestinal disorders, endocrine disruption, and increased cancer risk. Communities dependent on shallow groundwater sources are particularly vulnerable (FAO, 2019).

Furthermore, imbalanced fertilization degrades soil health, reducing soil organic matter and microbial diversity. This degradation results in declining crop quality and yield instability, indirectly affecting food availability and dietary diversity, thereby increasing nutritional insecurity and associated health risks (Bhattacharyya *et al.*, 2019; Zhang *et al.*, 2025).

Table 4: Adverse impact of imbalanced use of fertilizers on human health.

Human Health Aspect	Imbalanced Fertilizer Practice	Effect on Crop / Environment	Adverse Human Health Outcomes	Key References
Nitrate Toxicity	Excessive nitrogen application	High nitrate accumulation in vegetables and water bodies	*Methemoglobinemia* (blue baby syndrome), reduced oxygen transport	FAO (2019); Fixen (2015)
Micronutrient Deficiency	N-dominant fertilization with omission of Zn, Fe, S	Reduced micronutrient density in staple crops	Hidden hunger, impaired immunity, anemia	Magen (2008); FAO (2019)
Heavy Metal Exposure	Use of contaminated or excessive phosphate fertilizers	Increased Cd and Pb uptake by crops	Kidney damage, bone disorders, carcinogenic risks	Krasilnikov *et al.* (2022)
Water Quality Degradation	Nutrient leaching and runoff	Nitrate-contaminated drinking water	Gastrointestinal disorders, thyroid and cancer risks	FAO (2019); Fixen *et al.* (2015)
Food Safety & Quality Decline	Nutrient imbalance causing poor grain filling	Inferior protein and starch quality	Poor dietary quality and metabolic stress	Trivedi *et al.* (2020)
Immune System Suppression	Micronutrient-poor food production	Lower Zn and Fe intake	Increased susceptibility to infections	Magen (2008); Yousaf *et al.* (2020)
Chronic Disease Risk	Long-term exposure to nutrient-imbalanced diets	Poor nutritional balance	Increased risk of anemia, osteoporosis, metabolic disorders	Bhattacharyya *et al.* (2019)
Indirect Food Insecurity	Soil degradation and yield instability	Reduced food availability and diversity	Malnutrition and long-term public health stress	Zhang *et al.* (2025); FAO (2019)

Overall, the adverse health impacts of imbalanced fertilizer use underscore the necessity of transitioning toward soil test–based, balanced nutrient management strategies to protect both agricultural sustainability and public health (Table 4).

Linkage of Balanced Fertilizer Practices with SDGs and Food Security

The comparative evidence between balanced and imbalanced fertilizer practices has direct and significant implications for achieving multiple United Nations Sustainable Development Goals (SDGs), particularly those related to food security, sustainable agriculture, environmental protection, and human well-being. Balanced fertilization emerges as a critical intervention for aligning agricultural productivity with long-term sustainability objectives.

SDG 2: Zero Hunger

SDG 2 aims to end hunger, achieve food security, and promote sustainable agriculture. Balanced fertilizer use directly contributes to this goal by enhancing yield stability, crop quality, and nutrient density across major food and cash crops. Global evidence shows that balanced fertilization increases yields by 20–40% while preventing long-term soil degradation, thereby ensuring consistent food production over time (FAO, 2019; Zhang *et al.*, 2025). In contrast, imbalanced fertilization undermines food security by causing yield declines and soil nutrient depletion, particularly in intensively cultivated regions. By sustaining productivity and improving nutritional quality, balanced fertilization supports both food availability and food utilization—two core pillars of food security.

SDG 12: Responsible Consumption and Production

Balanced fertilizer management aligns with SDG 12 by promoting efficient nutrient use and minimizing wastage associated with excessive or mismanaged fertilizer application. Imbalanced nitrogen-dominant fertilization leads to low nutrient use efficiency, environmental losses, and declining soil fertility (Krasilnikov *et al.*, 2022). Balanced fertilization, guided by soil testing and crop requirements, optimizes input use, reduces nutrient losses, and enhances resource efficiency, contributing to more sustainable production systems.

SDG 13: Climate Action

Soil health improvements under balanced fertilization contribute to climate change mitigation and adaptation, central to SDG 13. Long-term studies demonstrate that balanced nutrient management increases soil organic carbon stocks, enhances soil structure, and improves water-holding capacity, thereby increasing resilience to climate variability such as droughts and floods (Bhattacharyya *et al.*, 2019; Zhang *et al.*, 2025). In contrast, imbalanced fertilization accelerates soil degradation and reduces ecosystem resilience, making farming systems more vulnerable to climate shocks.

SDG 15: Life on Land

Balanced fertilization supports SDG 15 by preserving soil biodiversity and ecosystem functions. Research shows that balanced nutrient application enhances microbial diversity, soil enzyme activity, and nutrient cycling, which are essential for maintaining healthy terrestrial ecosystems (Krasilnikov *et al.*, 2022). Imbalanced fertilizer use, particularly excessive nitrogen application, disrupts soil biological processes and contributes to land degradation, threatening long-term agricultural sustainability.

Food Security and Nutrition Nexus

Beyond yield, balanced fertilization improves crop nutritional quality, including higher protein content, micronutrient density (e.g., zinc in rice), and better fiber and sugar quality in cash crops. These improvements directly address issues of hidden hunger and malnutrition, especially in developing countries where diets rely heavily on staple crops (Magen, 2008; FAO, 2019). By improving both the quantity and quality of food produced, balanced fertilization strengthens food security across all four dimensions: availability, access, utilization, and stability.

Policy and Development Implications

The global evidence reviewed in this study highlights that transitioning from imbalanced to balanced fertilizer practices is not merely an agronomic choice but a strategic development intervention. Policies promoting soil test–based fertilizer recommendations, integrated nutrient management, and farmer education can accelerate progress toward SDGs while ensuring long-term food security. Balanced fertilization thus represents a scientifically validated pathway for achieving sustainable agricultural intensification without compromising environmental integrity.

Implications for Sustainable Agriculture and Food Security

The collective evidence from long-term and multi-location studies worldwide confirms that balanced fertilizer use is a cornerstone of sustainable agricultural intensification. Balanced fertilization simultaneously enhances crop yield, improves nutritional quality, and restores soil health—three interlinked pillars essential for ensuring global food security. Meta-analyses and long-term trials indicate that balanced nutrient management increases crop productivity by 20–40% while maintaining soil fertility, particularly in regions facing chronic nutrient depletion (FAO, 2019; Zhang *et al.*, 2025).

In developing regions of South Asia and sub-Saharan Africa, soil nutrient mining and unbalanced fertilizer use have been identified as major constraints to food security. Studies show that balanced fertilization significantly improves nutrient use efficiency (NUE), reducing fertilizer losses by 15–30% compared to nitrogen-dominant practices, thereby increasing the amount of food produced per unit of input (Fixen *et al.*, 2015). Improved NUE directly contributes to food availability and affordability, especially for smallholder farmers with limited access to inputs.

Balanced fertilization also plays a critical role in improving food quality and nutrition, addressing not only caloric availability but also micronutrient deficiencies—often referred to as "hidden hunger." Research has demonstrated that balanced fertilization increases protein concentration in cereals, zinc content in rice, and overall nutrient density in staple crops, contributing to improved dietary quality and human health outcomes (Magen, 2008; FAO, 2019; El-Nasharty *et al.*, 2022). These improvements strengthen the utilization pillar of food security by ensuring that food consumed meets nutritional requirements.

From an environmental perspective, balanced fertilizer use supports sustainable agriculture by reducing soil degradation and minimizing negative externalities associated with excessive fertilizer application (Xing, 2025). Long-term experiments reveal that balanced fertilization increases soil organic carbon stocks by 0.3–0.5%, improves soil structure, and enhances microbial activity, thereby increasing resilience to climate variability such as drought and extreme rainfall events (Bhattacharyya *et al.*, 2019; Krasilnikov *et al.*, 2022). These soil improvements are essential for maintaining long-term productivity under changing climatic conditions.

Balanced nutrient management is also strongly aligned with global sustainability and development frameworks. By improving nutrient use efficiency and reducing nutrient losses to water bodies and the atmosphere, balanced fertilization contributes to environmentally responsible production systems, supporting climate mitigation and land conservation goals (Fixen *et al.*, 2015). Consequently, international organizations and research institutions advocate soil test–based fertilizer recommendations and integrated nutrient management (INM) as core strategies for sustainable food systems (IPI, 2025).

Policy-oriented research further suggests that adoption of balanced fertilizer practices can enhance farm profitability while safeguarding natural resources. Economic analyses indicate that balanced fertilization increases net farm returns by 10–25% due to higher yields, improved quality premiums, and reduced input wastage (FAO, 2019). These economic benefits are crucial for encouraging farmer adoption and ensuring the long-term viability of sustainable agriculture initiatives.

Overall, global evidence clearly demonstrates that balanced fertilizer use is not merely an agronomic practice but a strategic intervention for sustainable agriculture and food security. By integrating productivity, nutritional quality, soil health, and environmental protection, balanced fertilization offers a scientifically validated pathway toward resilient food systems capable of meeting present and future global food demands.

CONCLUSION

Global evidence confirms that balanced fertilizer use is essential for sustainable crop production, improved food quality, and long-term soil health. Across major cropping systems, balanced nutrient management increased yields by 18–40% while enhancing protein content, micronutrient density, and carbohydrate quality. In contrast, nitrogen-dominant fertilization produced short-term gains but led to yield declines, soil degradation, and reduced crop quality over time, demonstrating that nutrient balance, not quantity, governs yield sustainability.

Beyond productivity, balanced fertilization improves human nutrition by promoting amino acid synthesis, enhancing energy metabolism, and increasing the bioavailability of essential nutrients such as phosphorus, potassium, iron, zinc, and boron in food crops. These improvements strengthen the soil–plant–human nutrient continuum, contributing to better nutritional security and public health outcomes.

Overall, balanced fertilizer management should be central to agricultural policy and extension efforts. Adoption of soil test-based and integrated nutrient management practices is critical for sustainable intensification, resilient food systems, and long-term global food security.

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Conflict of Interest

The authors declare no conflicts of interest regarding the publication of this manuscript. All ethical guidelines, including data privacy, research integrity, and publication ethics, have been strictly followed.

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