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Balancing chemical fertiliser application for optimal maize yield and environmental safety

Magdoline Mustafa Ahmed Osman[1,2,3*] – Ronald Kuunya[1,2] – Rania Alrasheed[3,4] – Erastus Wasikoyo[1,2] – András Tamás[1,2] – Árpád Illés [1,2] – Péter Ragán[1,2] – Tamás Rátonyi[1]

[1]Institute of Land Use, Engineering and Precision Farming Technology, Faculty of Agricultural and Food Sciences and Environmental Management, University of Debrecen, 138 Böszörményi street, 4032, Debrecen, Hungary

[2]Kálmán Kerpely Doctoral School, University of Debrecen, 138 Böszörményi Street, 4032 Debrecen, Hungary

[3]Environment, Natural Resources and Desertification Research Institute, National Centre for Research, Khartoum, Sudan

[4]Department of Plant Science, McGill University, Macdonald Campus, 21,111 Lakeshore Road, Sainte-Anne-de Bellevue, QC, Canada

*Correspondence: magdoline.osman@agr.unideb.hu

SUMMARY

Chemical fertilisers play a crucial role in enhancing maize productivity by supplying essential nutrients, particularly nitrogen, phosphorus, and potassium. However, excessive and imbalanced application of these fertilisers may result in soil degradation and environmental pollution. This review presents a comprehensive, bibliometric, and literature-based analysis of research on the balanced use of chemical fertilisers in maize production, spanning 2000 to 2025, and uses VOSviewer 1.6.20 as the analytical tool. The study analysed data from the Web of Science to examine publication trends, the configuration of keyword networks, and the dynamics of international research collaborations. The Mann-Kendall test revealed a significant positive trend ($p = 0.001$) in the volume of publications focused on chemical fertiliser balancing, with a coefficient of determination (R^2) of 0.5153. A total of 549 relevant studies were identified globally, with no language restrictions applied, indicating sustained growth in research output over time. Field studies demonstrate that reducing chemical fertiliser use by up to 25% when combined with biological amendments can maintain or enhance yields across diverse agroecological conditions. The emphasis is placed on sustainable fertilisation practices that balance productivity and environmental safety, highlighting challenges and future directions for adoption. Balanced fertiliser management is crucial for sustainable maize production systems, which simultaneously contribute to food security and environmental conservation. This study is significant as it systematically maps the evolution and current state of research on balanced chemical fertiliser use in maize production, providing valuable insights into publication trends, collaborative networks, and practical agronomic outcomes. Despite the progress, there remains a significant gap in region-specific guidelines and long-term impact assessments of integrated fertiliser management practices, which future research should address to optimise sustainable maize production tailored to diverse agro-ecological zones.

Keywords: *maize; synthetic fertilisers; productivity; environmental safety*

INTRODUCTION

Maize (*Zea mays* L.), commonly referred to as corn, is a cereal grain within the Gramineae/Poaceae family, often termed the 'Queen of Cereals' due to its diverse applications and superior yield potential among cereals. Globally, maize is cultivated on 192.01 million hectares, yielding 1,123.6 million metric tonnes at a productivity of 5.85 metric tonnes per hectare, serving both animal and human consumption. In contrast, within India, maize is cultivated on 27.72 million hectares, producing 3.07 million metric tonnes, with a similar productivity rate of 5.85 metric tonnes per hectare (Saritha et al., 2020).

Nutrient management is a pivotal factor influencing maize yield and quality (Batool, 2023; Osman et al., 2025). Fertiliser application accounts for up to 50% of the total increase in crop yields in contemporary agricultural practices (Zhang et al., 2017). The application of fertilisers ensures that maize plants absorb adequate nutrients from the soil throughout their growth, supporting biomass accumulation and the development of photosynthetic organs (Gaudin et al., 2015; Shibasaki et al., 2021). Current research indicates that the application of nitrogen, phosphorus, and potassium fertilisers significantly enhances soil fertility (Alvarez and Steinbach, 2017; Mbuthia et al., 2015).

While chemical fertilisers can significantly enhance crop yields in a relatively short timeframe compared to organic fertilisers, their use raises several environmental concerns (Chen et al., 2018; Chandini et al., 2019). Over-reliance on synthetic fertilisers can lead to soil degradation, reduced biodiversity, increased greenhouse gas emissions, and water pollution (Usman et al., 2018; Ononogbo et al., 2024). Excessive application may result in nutrient runoff, contaminating nearby water bodies and causing eutrophication (Khan and Mohammad, 2013; Akinnawo, 2023). This process depletes oxygen in water, harming aquatic life and disrupting ecosystems. Additionally, the production of chemical fertilisers is energy-intensive, contributing to greenhouse gas emissions such as nitrous oxide, carbon dioxide, and ammonium oxide into the atmosphere, thereby exacerbating global warming and climate change (Dutta et al., 2023; Zhang et al., 2013).

Sustainability concerns associated with chemical fertilisers have prompted a shift towards more eco-friendly alternatives. The need for integrated nutrient management practices that combine various fertiliser types is increasingly recognised to mitigate these negative impacts while maintaining agricultural productivity (Wu and Ma, 2015). Optimising fertiliser inputs to increase crop production efficiency and reduce environmental impact is complex, and efforts

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are complicated by interactions and variability among plant, nutrient, edaphic, and climatic factors (Giller et al., 2011; Morris et al., 2018; Schut and Giller, 2020).The utilization of both organic and chemical fertilizers, as well as the exclusive use of chemical fertilizers, has been documented to decrease the total nitrogen content in soil (Li et al., 2022; Pardo et al., 2009). Continuous application of synthetic nitrogen fertilizers has been associated with a decline in total soil nitrogen and soil organic carbon in long-term cereal studies, aligning with nitrification-induced losses and the depletion of soil organic matter (Guan et al., 2020). Prolonged nitrogen applications have been observed to elevate gross mineralization and nitrification rates, and are linked to increased gaseous nitrogen emissions, suggesting enhanced pathways for nitrogen loss from the soil reservoir (Han et al., 2024). Additionally, fertilisation can alter soil chemical properties and affect soil moisture (Kiboi et al., 2019; Paradelo et al., 2019).

This review highlights progress in optimising chemical fertiliser use for maize, addressing agronomic advantages, environmental concerns, and sustainable alternatives that promote resilient production systems. Although research is extensive, knowledge gaps persist regarding the prolonged effects of integrated nutrient management across varied agro-ecological zones and the socioeconomic challenges hindering sustainable fertilisation adoption. Filling these gaps is essential for creating tailored nutrient management strategies that enhance food security and support climate-smart agriculture. We performed a bibliometric study of maize-related chemical/inorganic fertiliser research from 2000 to 2025 using Web of Science data. The study examined publication patterns, collaboration networks, keyword relationships, and citation trends through VOSviewer, focusing on: (1) the global literature landscape and existing research deficiencies; (2) environmental consequences of chemical fertilisers; and (3) potential for developing region-specific recommendations.

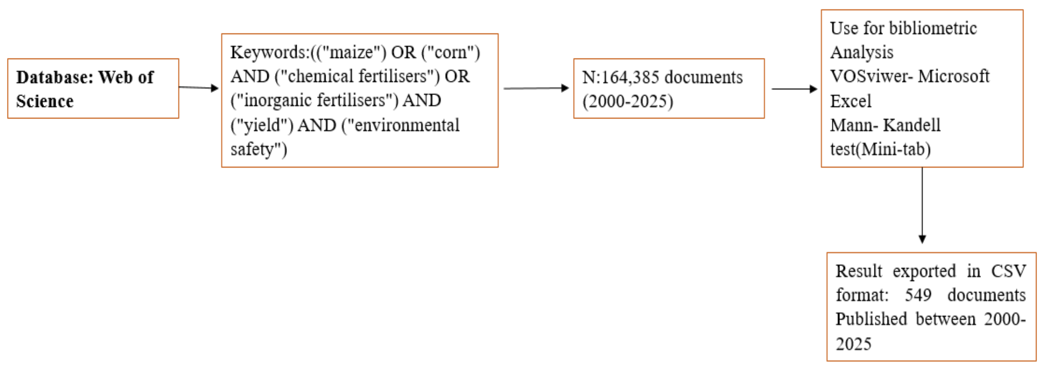
MATERIALS AND METHODS

Data Sourcing and Analytical Extraction

In this review, the authors have chosen the Web of Science (WoS) database, acknowledging its well-established reputation, authority, and extensive use as a resource for research publications and citations. WoS acts as a comprehensive repository of peer-reviewed articles and offers a user-friendly interface, which facilitates bibliographic literature reviews and data visualisation through tools such as VOSviewer1.6.20 software (Duque-Acevedo et al., 2020).

The review process was conducted in several stages (*Figure 1*). Initially, the authors performed a comprehensive search of the WoS database for scientific literature related to maize research that employed chemical fertilisers to enhance productivity. The search string utilised was: (("maize") OR ("corn") AND ("chemical fertilisers") OR ("inorganic fertilisers") AND ("yield") AND ("environmental safety")). When searched by topic (title, abstract, and keywords), this query retrieved 164,385 documents, which were too numerous to manage. Consequently, the search was restricted to the title field, resulting in 70,760 papers. Further filtering by year (2000–2025) narrowed the count to 51,444 documents, and additional refinement by research area (agriculture) resulted in 21,043 documents; restricted by publisher, resulting in 4,848 documents; restricted by open access (gold), resulting in 549 papers. The search was conducted on 21st November 2025, ensuring that the most recent publications indexed in WoS within the past 26 years were included.

Figure 1. **Data extraction process from Web of Science between 2000–2025**



Among the selected publications. The authors conducted a manual screening of these documents based on specific inclusion and exclusion criteria. Studies were included if they contributed to maize research on yield (both quality and quantity), soil fertility, and inorganic fertilisers. Papers focusing on maize diseases and disease management were excluded. This selection process resulted in 549 documents, published between 2000 and 2025. It is important to note that this study relied exclusively on the WoS database, which may have excluded relevant

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articles indexed in other databases such as Scopus or Google Scholar.

Data extraction and analysis

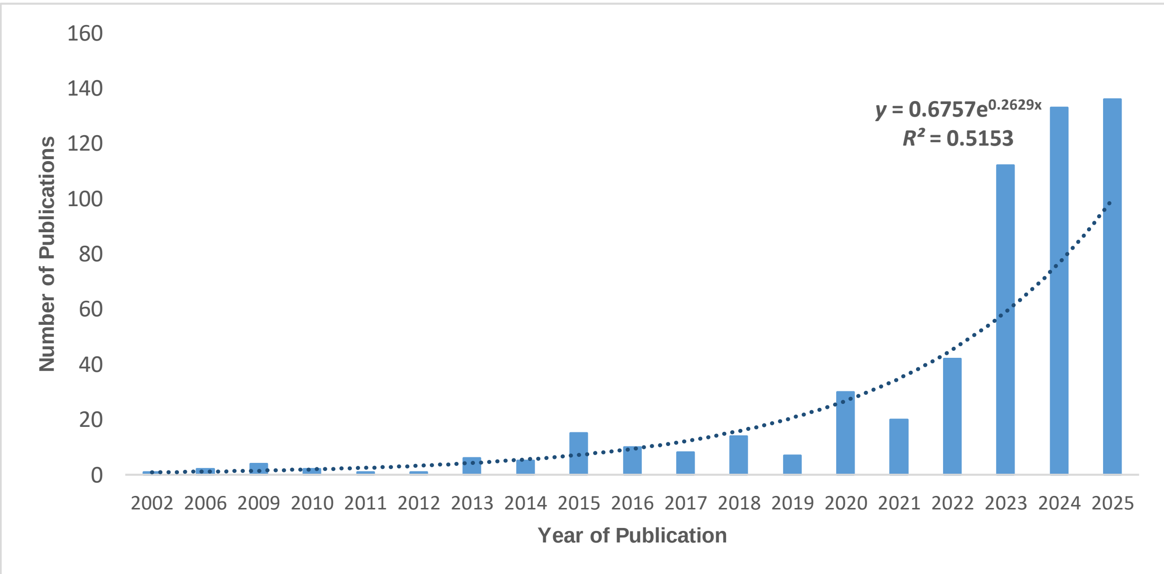
Involved exporting the metadata for the 549 documents from the Web of Science database in CSV format. The publication counts were then converted into Microsoft Excel format, where publication trends were examined using Excel's analytical functions. Bibliometric analyses were conducted with the VOSviewer software (Van Eck and Waltman, 2010). The principal units of bibliometric evaluation included co-authorship (by organisations and countries), co-occurrence (of author keywords and all keywords), and citation analysis (by authors and documents). The bibliometric indicators were visualised using VOSviewer's network mapping functions, enabling the identification of co-authorship networks, thematic clusters, and keyword co-occurrence relationships.

RESULTS AND DISCUSSION

Research publication trend in balancing chemical fertilisers

Over recent years, there has been a discernible increase in scholarly investigations into the effects of inorganic fertilisers on maize production. While research in this domain was relatively sparse in the early 2000s, a marked increase in interest has been observed from 2015 onwards. This trend is particularly pronounced in the years 2023, 2024, and 2025, which collectively account for 69.4% of the articles reviewed (*Figure 2*). These years underscore a pronounced focus on the potential of inorganic fertilisers to enhance fertiliser management practices, improve nutrient efficiency, and mitigate adverse environmental impacts. The data suggest a shift in research priorities, with an increasing emphasis on sustainable agricultural practices, the optimisation of synthetic fertiliser use, and the maintenance of soil health.

Figure 2. **Publications trend of chemical fertilisers in maize production**



Geography of publications on chemical fertilisers

The selected articles for this review encompass a range of global regions, with experts providing insights into the effects of chemical fertiliser usage (*Figure 3*). Notably, the majority of the research was conducted in Asia (55.3%), Europe (24.1%) and North America (16.7%). A smaller proportion of studies were carried out in Africa (5.3%) and Australia (3.8%), indicating a regional disparity in research emphasis and contributions to the field of fertiliser application (*Figure 3*). Among Asian countries, China is most significantly affected by synthetic fertilisers, as identified by Sun et al. (2012). The excessive application of these fertilisers has led to substantial soil acidification, heavy metal pollution, nitrate contamination in groundwater due to leaching and runoff, and eutrophication in aquatic systems such as rivers and lakes. In contrast, Europe applies considerably less fertiliser per hectare of cropland compared to Asia, where overuse results in nitrogen pollution exceeding 100 kg ha^{-1} in countries like China. N pollution exceeding 100 kg ha^{-1} typically refers to nitrogen fertiliser application rates surpassing crop uptake needs, leading to nutrient surpluses that leach into groundwater as nitrates or emit as N_2O gas, causing water contamination, eutrophication, and climate impacts. The European Union's mineral fertiliser consumption decreased to 9.8 million tonnes in 2022, a 10% reduction from 2021, reflecting a lower application rate compared to Asia's annual usage of over 90 million tonnes (https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20240628-1).

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Figure 3. **Distribution of publications on chemical fertilisers in the world**

Co-occurrence of keywords and thematic areas of research

Table 1 presents a co-occurrence analysis of author keywords from Web of Science (WoS) publications on maize research from 2000 to 2025. This analysis underscores the pivotal role of chemical fertilisers, particularly nitrogen, in optimising yield networks. The term "Maize" is central, appearing 118 times with a total link strength of 79, and frequently co-occurs with metrics related to fertiliser efficiency under conditions of water and soil constraints. The emphasis on nitrogen within chemical fertilisers is evident, as "Nitrogen use efficiency" is noted 11 times with a link strength of 12, and "Nitrogen" appears 6 times with a link strength of 5, both demonstrating significant associations with yield enhancement. The interactions between efficiency and soil are highlighted by the connections of "Nitrogen use efficiency" to "Soil fertility" (7 occurrences, 8 strength), "Soil quality" (5 occurrences, 5 strength), and "Soil organic carbon" (7 occurrences, 7 strength), indicating research efforts aimed at minimising chemical fertiliser losses. Furthermore, the intersection of chemical fertilisers with sustainability is illustrated by their links to "Climate change" (17 occurrences, 16 strength), "No tillage" (5 occurrences, 4 strength), and "Biochar" (10 occurrences, 6 strength), reflecting a trend towards reducing reliance on synthetic inputs.

Figure 4 presents a comprehensive keyword co-occurrence network analysis of the 191 most relevant keywords, each appearing at least twice across 549 articles. The network consists of 191 nodes, 4,302 links, and a total link strength of 7,620. Each node represents a keyword, with its size indicating the frequency of occurrence. According to Sellami and Terribile (2023), keywords with higher frequencies during specific time periods indicate topics of significant interest and focus at those times. The purple cluster, spanning 2000–2018, is characterised by frequent co-occurrence of keywords such as carbon, decomposition, soil organic carbon, nitrification, nitrate, fraction, phosphorus, soil properties, and transport. Overall, the network demonstrates that maize research is highly interdisciplinary, integrating agronomy, soil science, crop physiology, and modern analytical technologies. The strong connectivity among keywords suggests that improving maize yield is closely linked with efficient resource management, soil health, and advanced technological applications in crop production systems.

Figure 5 illustrates the temporal progression of authors' keywords within the co-occurrence network from 2021 to 2025. Our analysis indicates that keywords such as soil organic carbon, climate change, and food security were identified earlier (before 2021). Conversely, keywords related to maize production, including grain yield, remote sensing, and nitrogen, gained prominence later (in 2023). A significant opportunity exists to investigate the effects of integrated practices on balanced chemical fertiliser use, as well as to study crops and regions that have received limited research attention in nutrient management.

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Table 1. **Co-occurrence of author keywords based on WoS between 2000–2025**

Keywords	Occurrences	Total link strength
Maize	118	79
yield	22	30
Water productivity	25	28
Grain yield	27	26
Evapotranspiration	14	18
Climate change	17	16
Water use efficiency	15	16
Nitrogen use efficiency	11	12
Soil water content	8	12
Irrigation	11	10
Maize yield	23	10
Drip irrigation	5	9
Grain filling	6	9
Leaf area index	6	9
Remote sensing	10	9
Spring maize	7	9
Water use	5	9
photosynthesis	9	8
Soil fertility	7	8
Soil organic carbon	7	7
bio char	10	6
Food security	7	6
Machine learning	9	6
Soil moisture	5	6
Zea mays	12	6
Intercropping	6	5
Nitrogen	6	5
Soil quality	5	5
No tillage	5	4
Plant density	6	4
Root	6	4
Water stress	5	4
Root Growth	5	3

Figure 4. **All keywords Co-occurrence based on WoS between 2000–2025**

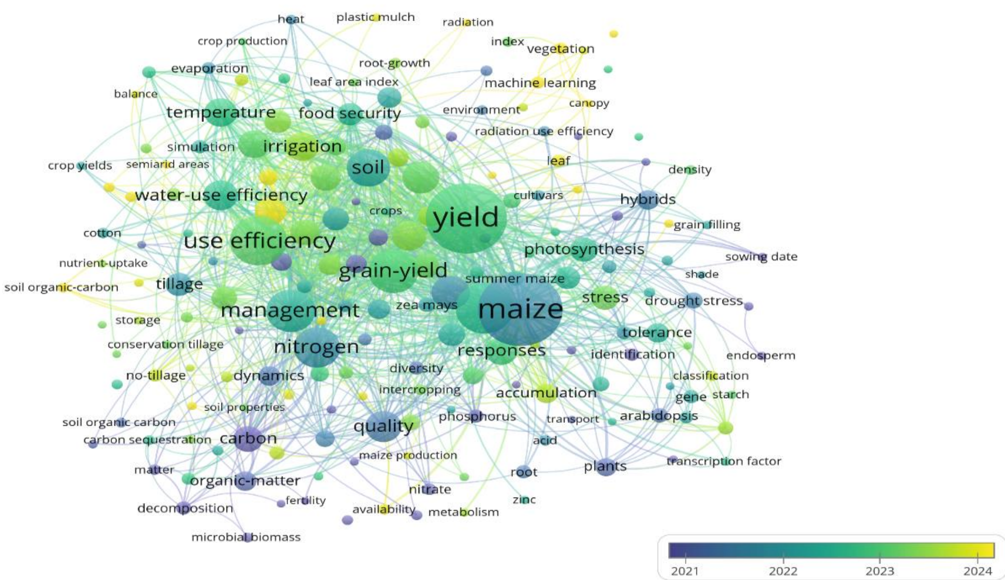

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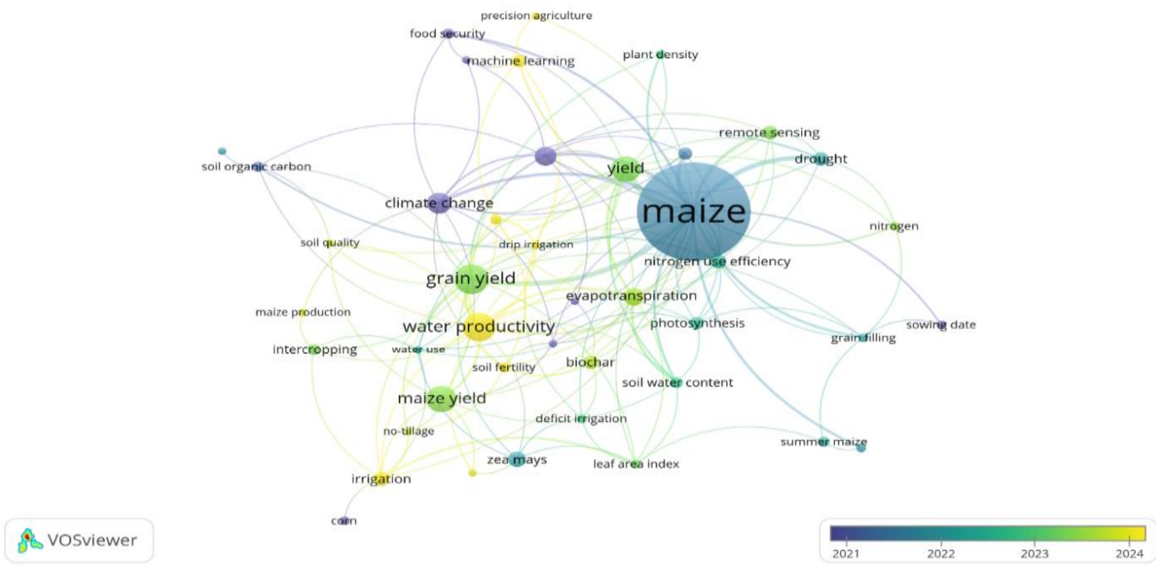
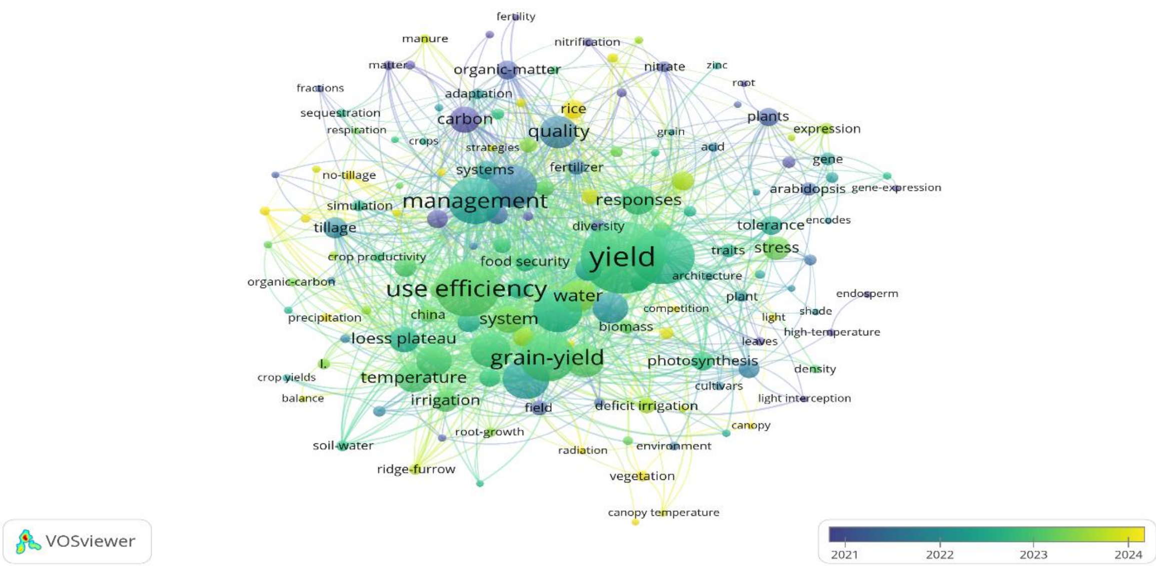
Figure 5. **Author keywords Co-occurrence based on WoS between 2000–2025**



The network in *Figure 6* depicts the co-occurrence of keywords in the literature on chemical fertiliser management and maize production. Each node corresponds to a keyword, with node size indicating frequency of occurrence, while links illustrate co-occurrence relationships between keywords. Central keywords such as yield, grain yield, use efficiency, management, and quality emphasise the focus on optimising maize productivity through improved nutrient management. Keywords such as fertiliser, nitrogen, irrigation, water, and soil indicate that nutrient and water management are closely studied to enhance fertiliser efficiency and crop performance. The strong interconnections between yield, management, and use efficiency suggest that studies increasingly focus on integrated fertiliser management to maximise maize productivity while minimising environmental impact.

Figure 6. **Keyword plus Co-occurrence based on WoS between 2000–2025**



Chemical fertilisers in maize production

Fertiliser application constitutes a critical artificial intervention, essential for providing crops with adequate nutrients to sustain high yields and ensure global food security (Liu et al., 2021). Fertiliser use contributes to up to 50% of the overall increase in crop yields in modern agricultural practices (Zhang et al., 2017). The application of fertilisers ensures that maize

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absorbs sufficient nutrients from the soil during its growth, supporting biomass accumulation and the development of photosynthetic organs (Gaudin et al., 2015; Shibasaki et al., 2021). Maize requires specific nutrients, including nitrogen (N), phosphorus (P), and potassium (K), as well as secondary and micronutrients, to grow and develop effectively and achieve optimal yield (Batool, 2023). The primary nutrients play distinct roles during maize growth. For example, fertilisers such as urea, ammonium nitrate, and ammonium sulfate are commonly used to supply maize with the essential nutrient nitrogen. It is recommended to apply nitrogen in multiple doses to align with the crop's requirements throughout the growing season (Song et al., 2020). Conversely, phosphorus fertilisers, such as diammonium phosphate (DAP) and triple superphosphate (TSP), are crucial for root development and overall plant growth (Batool, 2023). These fertilisers are typically applied during planting, either distributed across the field or placed in a band near the seed, due to phosphorus's immobility, to ensure efficient absorption by developing roots. Potassium fertilisers, such as potassium chloride (KCl) and potassium sulfate (K_2SO_4), are vital for enhancing maize yield and improving drought resistance (Nisa, 2021). Fertiliser application is an effective method to boost maize production (Wu et al., 2022). However, extensive fertiliser use exerts ongoing environmental pressure and conflicts with the national strategic plan to eliminate chemical fertilisers and pesticides by 2030 (Sainju et al., 2003; Wang et al., 2016, 2022). Chemical fertilisers provide readily available nutrients to the root zone, which are prone to losses, whereas biofertilizers enhance nutrient uptake by fixing nutrients susceptible to loss and from external sources (e.g., N2 fixing bacteria) or by solubilising unavailable nutrients (e.g., P and K solubilising bacteria) (Pawar et al., 2019). Current research indicates that the use of nitrogen, phosphorus, and potassium fertilisers significantly impacts soil fertility (Alvarez and Steinbach, 2017; Mbuthia et al., 2015). Therefore, achieving optimal and sustainable fertiliser management that balances chemical inputs with biological amendments is crucial for sustaining both maize productivity and environmental health (Abdo et al., 2022).

Impacts of chemical fertilisers

The utilisation of chemical fertilisers in maize cultivation has significantly enhanced crop yields by supplying essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K). Effective fertilisation not only augments soil nutrient levels but also improves water use efficiency and plant growth parameters, thereby enhancing maize productivity. Research, including meta-analyses and field studies, suggests that fertilisation can increase maize yields by 11.65% to over 200%, contingent upon the combination of mineral and organic fertilisers and soil conditions (Jiang et al., 2024). However, the excessive application of chemical fertilizers has resulted in considerable environmental challenges, including the eutrophication of surface waters, groundwater contamination, soil degradation, and greenhouse gas emissions from surplus nitrogen, which is either leached into water or released into the atmosphere as ammonia and N_2O, among other compounds (Yan et al., 2013; Norse and Ju, 2015; Zhou et al., 2018; Yang et al., 2022; Adnan et al., 2020). By integrating biofertilizers and growth stimulants, it is possible to reduce fertiliser input by 10–20% without compromising yield, thereby promoting sustainable maize production with diminished environmental impact (Zou et al., 2024). Consequently, although chemical fertilisers are indispensable for achieving high maize yields, their judicious use in conjunction with biological alternatives is vital for maintaining productivity while ensuring improved soil health and environmental protection (Abdo et al., 2022; Zou et al., 2024).

Optimisation strategies

Determining the appropriate quantity of fertiliser is essential for optimising maize production while minimising environmental impact and reducing input costs (Zou et al., 2024). Equally important is the timing of fertiliser application during the maize production season. Research has demonstrated that identifying the optimal fertiliser dosage tailored to specific local agroecological conditions can significantly enhance both yield and profitability. For example, studies indicate that approximately 150 kg ha^{-1} of NPSB (Nitrogen (N), Phosphorus (P), Sulfur (S), and Boron (B)**)** fertiliser is optimal for smallholder farmers in certain regions, achieving a balance between economic benefits and sustainable agriculture (Daemo et al., 2024). Applying fertilisers in split and staggered doses, aligned with the crop's growth stages, has been shown to improve nutrient-use efficiency by minimising losses from leaching and volatilisation (Ojeniyi et al., 2024). Both simulation and field trials have confirmed that administering about 80% of the total fertiliser amount, distributed across key maize growth stages, can maintain or even enhance biomass and grain yield while reducing environmental contamination (Deng et al., 2023). Furthermore, integrating chemical fertilisers with biofertilizers and growth enhancers presents a promising strategy for maintaining high yields with reduced chemical inputs. Research suggests that using 75% of the conventional NPK rate, combined with biofertilizers and foliar applications of amino acids and humic acids, improved nutrient uptake, plant growth, and yield to levels comparable to full chemical fertiliser rates, while mitigating environmental risks (Abdo et al., 2022). These integrated nutrient management strategies support sustainable maize production by enhancing nutrient availability, improving soil fertility, and increasing crop resilience, while minimising the ecological impact of fertilisation (Daemo et al., 2024).

Environmental safety measures

The environmental impacts of crop production are predominantly associated with the consumption of fossil fuels and the application of fertilisers (Bacenetti et al., 2016). Fertilisers are integral to agriculture,

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enhancing crop growth and increasing yields; however, their persistent use poses significant environmental risks. Consequently, it is imperative to thoroughly examine the extent of fertiliser usage and its potential ecological threats during crop production (Yang et al., 2024). Emissions from the application of both organic and mineral fertilisers substantially contribute to environmental issues such as eutrophication and acidification (Bacenetti et al., 2016). Nevertheless, the excessive use of fertilisers has resulted in nitrate-N becoming a common contaminant in water sources. Nitrate-N can be transported into adjacent rivers, lakes, or reservoirs through runoff from rain or irrigation, and it can also infiltrate groundwater through leaching (Barzegari et al., 2017; Zhang et al., 2021a; Zhang et al., 2021b). When nitrate-nitrogen concentrations exceed regulatory thresholds, groundwater becomes unfit for human consumption, including potable uses (Feng et al., 2020). Nitrate levels in drinking water are restricted to below 20 mg L^{-1} under China's National Standards for Drinking Water Quality (Ministry of Environmental Protection of the People's Republic of China). Globally, 60% of regions experiencing rising nitrate-N levels in groundwater are associated with agricultural lands (Shukla and Saxena, 2018). Contaminants such as heavy metals and nitrites can enter the food chain, raising cancer risks and impairing human health and well-being (Karwowska and Kononiuk, 2020). Inorganic fertilisers have nonetheless increased nitrate levels in water bodies (WHO, 2016). Dietary nitrate intake carries health risks; 60–70% is rapidly absorbed and excreted in urine (~3% as urea/ammonia), while some bypasses the stomach to reach circulation (Ding et al., 2018). Previous studies have demonstrated that alternate partial root-zone drip irrigation (ADI) or fertigation positively influences crop dry mass accumulation, yield, nitrogen (N) uptake, and water- and nitrogen-use efficiencies (WUE and NUE). Nevertheless, the synergistic benefits of combining ADI with fertigation on crop yield, N uptake, WUE, and NUE remain unresolved. Accordingly, the integrated application of ADI and optimised N fertigation will enhance N uptake, WUE, and NUE in sweet-waxy maize (Fu et al., 2017). Fertigation, which delivers mineral fertiliser through a drip system, provides more precise amounts of nutrients (e.g., N) and water to the active root zone of the plant compared to broadcast fertilisation (Abalos et al., 2014). Drip fertigation has been shown to reduce methane (CH_4) emissions and nitrogen losses (NH_3, N_2O, and NO) while increasing soil organic carbon (SOC) content (Bhat and Sujatha, 2009). Research also highlights that the integration of suitable irrigation methods and conservation agricultural practices with optimised nitrogen fertilisation can lower nitrous oxide emissions and improve water use efficiency, further reducing the negative environmental impact during maize production (Zhang et al., 2020). Collectively, these environmental protection measures foster a sustainable approach to maize cultivation, which balances productivity with the preservation of ecosystem health.

Case studies and regional research

Recent empirical investigations and experimental trials conducted across diverse regions have elucidated the effects of reducing and optimising chemical fertiliser usage on maize yield and soil health. In Nigeria's Middle Belt, research has demonstrated that the application of straight fertilisers in split doses, tailored to site-specific guidelines, significantly enhances maize nutrient use efficiency and yield compared to conventional blended fertilisers and local agricultural practices (Ojeniyi et al., 2024). Studies conducted in various regions, including Nigeria, Sub-Saharan Africa, and Asia, have consistently shown that improving fertiliser efficiency can substantially increase crop yields. However, the incorrect or excessive application of synthetic fertilisers can have detrimental effects. For instance, Devkota et al. (2016, 2018) found that in Nepal's Nawalparasi and Palpa districts, the adoption of balanced nutrient management and best practices resulted in more than a 100% increase in maize yield. Research in South Asia indicates that nutrient use efficiency can be further improved by applying nitrogen (N), phosphorus (P), and potassium (K) fertilisers in balanced ratios, combined with the strategic use of organic manures within farming systems (Jat et al., 2014). Similarly, Mahamood et al. (2017) reported a high corn grain yield of 8.37 t ha^{-1} with a balanced application of $N_{300}P_{50}K_{150}S_{30}$. In another study, Vanlauwe et al. (2011) underscored the importance of precise fertiliser application, noting that continuous cultivation with accurate nitrogen use significantly improved nitrogen-use efficiency compared to fields that were not consistently cultivated. Conversely, Meng et al. (2017) cautioned against the overuse of nitrogen fertilisers, particularly in China, where misconceptions about the nitrogen uptake-yield relationship have led to excessive and poorly timed fertiliser applications, ultimately disrupting the balance between crop nitrogen needs and supply. A separate study in China demonstrated that precision nutrient management can reduce NPK fertiliser application by approximately 8.83% to 19% without significantly affecting crop yield. This reduction contributes to decreased soil, water, and air pollution, supporting sustainable production goals. The optimal fertiliser application rate was identified as approximately 547 kg ha^{-1}, with no yield loss observed when the rate was reduced to 486 kg ha^{-1}. (Zou et al., 2024). Bamboriya et al. (2023) demonstrated that using 75% NPK fertilisers (e.g., 75 kg ha^{-1} vs. 100 kg ha^{-1} standard) as per STR (soil test response) + EPC (enriched phosphorus compost)+ Azotobacter, PSB (Phosphate Solubilising Bacteria), and a 0.5% foliar zinc ($ZnSO_4.H_2O$) spray can enhance soil health in maize-based cropping systems. These regional studies collectively highlight that optimized fertilizer strategies, such as split applications and precision nutrient management, enhance maize yields while preserving soil nutrient balance, improving soil health, and minimizing environmental impact; split applications divide fertilizer doses, primarily nitrogen, into multiple smaller amounts timed with crop growth

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stages to improve uptake and reduce losses, whereas precision nutrient management uses soil testing, GPS mapping, and sensors to tailor fertilizer application, optimizing input efficiency, reducing costs, and protecting the environment. Ongoing long-term monitoring is crucial to thoroughly evaluate soil health outcomes and to fine-tune fertiliser recommendations for specific agroecosystems. These outcomes typically include improvements in soil structure, nutrient availability, microbial activity, organic matter content, water retention, and overall fertility, which collectively support sustainable crop production and environmental quality.

Challenges and future directions

1. Small farm sizes, high upfront costs for precision tools, soil heterogenity, and limited extension services hinder the adoption of optimised fertiliser practices in maize production.
2. Reliance on blanket recommendations often exacerbates nutrient imbalances and environmental harm.
3. Deficiencies in knowledge among smallholder farmers, policy biases that favor chemical subsidies, and climate variability further hinder the implementation of integrated nutrient management. These factors diminish nutrient-use efficiency in regions such as Sub-Saharan Africa and Asia. Addressing these issues is crucial for prioritising interventions aimed at enhancing food security in densely populated, agriculture-dependent areas that face significant risks of malnutrition.
4. Future research endeavours should prioritise conducting long-term trials utilising models such as the Decision Support System for Agro-technology Transfer (DSSAT) and Crop Environment Resource Synthesis (CERES) Maize to simulate site-specific management strategies.
5. Combining reduced NPK fertiliser application with biofertilizers can sustain yields and improve soil health.
6. Affordable modern technologies, including low-cost sensors, mobile apps, and precision fertigation systems, paired with policy incentives, can scale precision agriculture.

CONCLUSIONS

Achieving a balance in the use of chemical fertilisers for maize cultivation is crucial for maximising crop yields while protecting the environment and ensuring sustainability over the long term. Studies confirm that optimising fertiliser application rates, using split and staggered dosing, and incorporating biofertilisers and organic amendments can greatly enhance nutrient use efficiency, boost crop productivity, and improve soil quality. Examples from various regions demonstrate that reducing chemical fertiliser inputs, when combined with precise nutrient management techniques, can maintain or even increase maize yields without degrading soil health. To further advance sustainable maize farming, challenges such as high input costs, lack of knowledge, and infrastructure limitations need to be tackled through focused research, technological advancements, and extension services. Recommendations stress the importance of balanced fertilisation strategies that integrate moderate chemical fertiliser use with organic inputs to preserve soil organic carbon, enhance nutrient cycling, and reduce nutrient losses. These integrated methods align productivity objectives with environmental conservation, supporting resilient and sustainable maize farming systems. Ongoing multidisciplinary efforts are essential for refining fertiliser practices to address future food security and ecological challenges.

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