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Soil, nutrient, and fertiliser requirements for maize (*Zea mays*) production: A narrative review

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SUMMARY

Maize (Zea mays) is a key staple crop essential for global food security, with its productivity heavily influenced by soil, nutrient, and fertiliser management. This review examines the requirements for optimal maize production by analysing recent literature on soil properties, nutrient uptake, and fertilisation practices. A systematic approach was used to gather relevant studies from Google Scholar, Scopus, and Web of Science, focusing on peer-reviewed articles, books, and conference proceedings published in the last 10 years. Keywords such as "maize soil requirements" and "nutrient management for maize" guided the search, and both global and region-specific research were included to capture diverse agricultural systems and environments. Key insights were extracted to understand best practices, challenges, and technological advancements influencing maize yield. The findings provide a comprehensive overview of the current state of knowledge on soil and nutrient management for maize cultivation, highlighting optimal practices and emerging trends in fertilisation techniques. The review aims to support improved management strategies for yield maximisation and sustainable maize production across various agricultural landscapes, ensuring food security in the face of changing environmental conditions.

Keywords: *maize production; soil fertility; nutrients; fertilisation practices; soil monitoring*

INTRODUCTION

Soil is a loose material on the Earth's surface containing mineral or organic matter (McBratney and Hartemink, 2024). Its components, namely solid, liquid, and gas, result from the interaction of the atmosphere, biosphere, lithosphere, and hydrosphere (Wang et al., 2015). Soil properties, including biological, chemical, and physical aspects, vary spatially due to internal and external factors in soil management (Abdu et al., 2023). Key chemical properties, such as cation exchange capacity (CEC), electrical conductivity, salinity, pH, organic matter, and fertility, significantly affect soil conditions (Sainju and Liptzin, 2022; Choudhary et al., 2023). CEC is crucial as it dictates the adsorption of cations, which influences nutrient availability for crops (Strawn, 2021; Hossain et al., 2020). The fertility level determines nutrient requirements for crops, such as maize, which has specific nutrient needs corresponding to its growth potential (Ahmed et al., 2021; ten Berge et al., 2019). Fertilisers are applied to fill nutrient gaps and address deficiencies (Bucagu et al., 2020).

Maize (*Zea mays*) is a major staple crop that thrives in various soil conditions, though optimal growth requires careful soil management (Bhat et al., 2024). Factors affecting maize cultivation include soil texture, structure, pH, nutrient availability, and organic matter content. Monitoring soil variability is crucial for maximising yields and promoting sustainable agriculture (Stadler et al., 2015). The ratio of sand, silt, and clay affects water retention, aeration, and nutrient availability. Loamy soils, which have a balanced mix of these particles, are ideal for maize, offering good drainage and moisture retention (Lippold et al., 2022). Maize prefers a slightly acidic to neutral pH range (6.0–7.5) for optimal nutrient availability, especially for phosphorus (Agegnehu et al., 2021). Regular monitoring of pH ensures proper lime application to correct acidity (Ejigu et al., 2023). Maize requires substantial macro- and micronutrients, and soil tests help identify deficiencies, guiding fertiliser application (Njoroge et al., 2018). Higher organic matter improves soil structure, water retention, and microbial activity, essential for soil health and crop growth (Celestina et al., 2019; Goldan et al., 2023). Regular assessments of organic matter can guide compost and manure applications. Adequate moisture is critical, particularly during key growth stages, and monitoring soil moisture helps optimise irrigation and reduce water stress (Lamlom et al., 2024).

Understanding soil variability is essential for precise agricultural management. Traditional soil sampling and laboratory tests, while useful, are labor-intensive and may not capture spatial variability effectively (Lawrence et al., 2020). Therefore, advanced methods for monitoring soil variability have been adopted (Zhang et al., 2024). In conclusion, managing soil properties is crucial for optimising maize growth and ensuring sustainable agriculture. Chemical, biological, and physical properties, including pH, nutrient availability, organic matter, and texture, directly impact maize health and yield. While traditional soil testing remains important, precision agriculture technologies such as remote sensing, GIS, and soil moisture sensors offer real-time assessments of soil conditions, enabling targeted interventions like variable-rate fertilisation and irrigation (Getahun et al., 2024). These tools help farmers optimise maize productivity, tailor fertilisation schedules, reduce environmental impact, and ensure sustainable, profitable production. A combination of traditional soil testing and innovative technologies will enhance soil health and maize productivity in the long term.

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METHODOLOGY

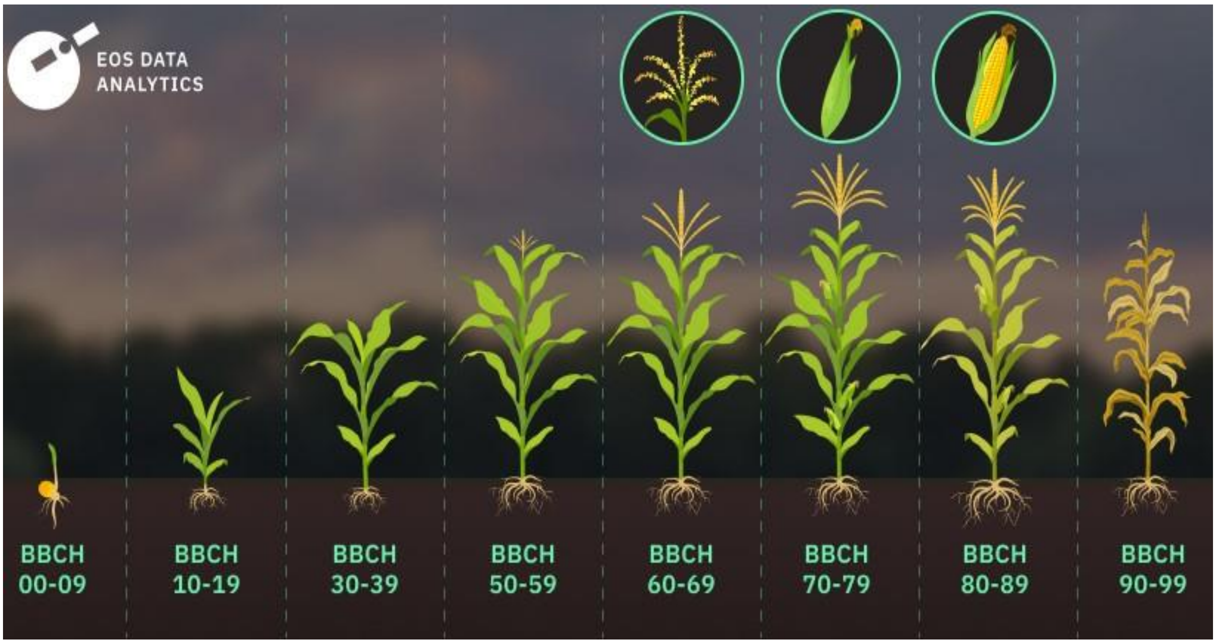
A systematic approach was followed to obtain relevant literature on soil, nutrient, and fertiliser requirements for maize (*Zea mays*). Initially, a broad search was conducted using three academic databases, namely Google Scholar, Scopus, and Web of Science, focusing on peer-reviewed articles, books, and conference proceedings. The search terms included keywords like "maize soil requirements," "nutrient management for maize," "fertiliser application for maize," "soil variability monitoring in maize fields," and "soil fertility in maize production." The inclusion criteria involved studies published within the last 10 years to ensure the most current practices and technologies are considered. Both global and region-specific studies were selected to capture diverse environmental conditions and farming practices. The selected literature was scrutinised for relevant information on soil properties, nutrient uptake, fertilisation practices, and technological advancements. Literature from various research articles was synthesised to provide a comprehensive narrative on the topic.

RESULTS AND DISCUSSION

Multi-phase nutrient interventions for maize crop on varying soil status

A full soil test is carried out at pre-planting phase with the aim of analysing the availability of its nutrients (Fageria and Nascente, 2014). Test precedes a recommendation of the required fertiliser and fertiliser rates that can favour either the soil or the maize crop or a combination (Zerssa et al., 2021). Additionally, the levels of soil pH may be adjusted and optimised for proper growth of the crop; this can be done by applying lime (such as dolomite) or Sulphur products (Sparks et al., 2024). *Figure 1* shows the growth phases of a maize plant.

Figure 1. **Growth phases of a maize plant according to the BBCH (Biologische Bundesanstalt, Bundessortenamt und CHemische Industrie) scale**



BBCH 00-09 (Germination and seedling stages); BBCH 10-19 (Development of leaves); BBCH 30-39 (Stages of vegetative growth); BBCH 50-59 (Emergence of inflorescence); BBCH 60-69 (Flowering stage); BBCH 70-79 (Fruiting stage); BBCH 80-89 (Ripening stage); and BBCH 00-09 (Senescence and maturity stage)

Source: End of season (EOS) Data Analytics – Crop Management Guide

Nitrogen and phosphorus are essential for maize during early growth, particularly in the Seeding and Germination phase, supporting root system development and healthy seedlings (Battisti et al., 2023; Blandino et al., 2022; Razaq et al., 2017; Khan et al., 2023). Proper soil preparation and fertilisation are crucial at this stage (Battisti et al., 2022). During the vegetative growth phase, maize rapidly develops reproductive and propagation structures, with high nutrient demands for nitrogen, phosphorus, potassium, zinc, and manganese (Pasley et al., 2019; Bojtor et al., 2021; García et al., 2023; Capo et al., 2024; Ferreira et al., 2024). A soil test to 50-cm depth helps determine nitrogen availability in the root zone, optimising fertilisation and saving costs (Zhang et al., 2022; Chen et al., 2022). The Tasseling and Pollination phase is critical for maize, requiring sufficient nitrogen and boron for pollination and grain formation (Zhang et al., 2014; Rerkasem et al., 2020; Bienert et al., 2023). Foliar analysis aids in regulating nutrient supply for optimal pollination (Lv et al., 2021; Grzebisz and Łukowiak, 2021). During the

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Silking and Grain-filling phase (55–66 days after emergence), adequate nitrogen, phosphorus, potassium, and magnesium are vital for grain development and yield (Li et al., 2023; Li et al., 2024; Thompson et al., 2023; Khan et al., 2014; Kumari et al., 2022; Gerendás and Führs, 2023; Yahaya et al., 2023). At the Maturation and Harvesting phase, nutrient needs decline due to reduced growth (Adelabu and Modi, 2017; Akinnuoye-Adelabu et al., 2019; Maresma et al., 2019; Djaman et al., 2022; Cao et al., 2024; Zhao et al., 2024). Nutrient analysis helps determine nutrient offtake and identify limiting nutrients (Finch et al., 2014; Yan et al., 2022). Aflatoxin levels in harvested grains should be measured to prevent health risks like liver injury (Wacoo et al., 2014; Kumar et al., 2021; Hua et al., 2020).

Nutrient requirements for maize

The crop is nutrient-demanding crop, and the soil plays a crucial role in providing the essential nutrients for its growth and development (Dawar et al., 2022). This is in terms of vegetative growth, chlorophyll production, protein synthesis, root development, flowering, seed formation, water regulation, enzyme activation, photosynthesis, and supporting various physiological functions and improving overall plant health. Specifically, to maize, the key nutrients that can be suitably provided by the soil are in both groups of macro- and micro-nutrients (Grabovskyi et al., 2023):

Macro-nutrients provided to maize crop

Nitrogen (N) is crucial for vegetative growth, forming amino acids and proteins. It promotes green foliage and is essential in early growth stages, supplied by organic matter, plant residue decomposition, and biological fixation by legumes. Phosphorus (P) supports root development, energy transfer, photosynthesis, and DNA/RNA formation. It is provided by phosphate minerals ($Ca_5(PO_4)_3$) and organic matter in soil. Potassium (K) regulates water, activates enzymes, and aids photosynthesis, enhancing plant health and disease resistance. It is sourced from potash minerals and decomposed organic matter. Calcium (Ca), a secondary nutrient, strengthens cell walls, supports enzyme activity, and facilitates nutrient movement. It is found in limestone ($CaCO_3$) and gypsum ($CaSO_4 \cdot 2H_2O$). Magnesium (Mg), a key chlorophyll component, is vital for photosynthesis and enzyme functions, supplied by minerals like dolomite ($CaMg(CO_3)_2$) and serpentine ($Mg_3Si_2O_5(OH)_4$). Sulphur (S) is essential for protein synthesis and enzyme function, available in soil organic matter and as sulphate from weathered minerals (ten Berge et al., 2019). *Table 1* shows the average macro-nutrient percentage base available for a maize crop (Ray et al., 2020; Bojtor et al., 2021).

Table 1. **Summary of average macro-nutrient percentage base for a maize crop**

Macro-nutrient	Average nutrient percentage
Nitrogen (N)	40–50%
Phosphorus (P)	10–15%
Potassium (K)	30–40%
Calcium (Ca)	2–5%
Magnesium (Mg)	2–5%
Sulphur (S)	1–3%

Micro-nutrients provided to maize crop

These nutrients are summarised in *Table 2.* Iron (Fe) is vital for chlorophyll synthesis and enzyme activity, crucial for photosynthesis. It is commonly found in soil organic matter and iron-rich minerals. Zinc (Zn) supports growth hormone production and enzyme function, with deficiencies causing stunted growth and poor kernel development. Zinc is available in organic matter and minerals like sphalerite (ZnS), smithsonite ($ZnCO_3$), zincite (ZnO), and franklinite ($ZnFe_2O_4$). Manganese aids in photosynthesis and the metabolism of nitrogen and phosphorus, found as oxides and organic complexes like magnesium chelate – EDTA. Copper (Cu) is important for reproductive growth and photosynthesis, involved in enzyme processes, and is found in trace amounts in soil minerals. Boron (B) is essential for cell wall formation and reproductive development, aiding pollen germination and seed development in maize. It is available in limited quantities from organic matter and certain minerals like Borax ($Na_2B_4O_7 \cdot 10H_2O$), Colemanite ($Ca_2B_6O_{11} \cdot 5H_2O$), and Ulexite ($Na_2CaB_5O_9 \cdot 8H_2O$) (Stewart et al., 2021; Korzeniowska & Stanislawska-Glubiak, 2022).

Table 2. **Summary of average micro-nutrient percentage base for a maize crop**

Micro-nutrient	Average nutrient percentage
Iron (Fe)	0.01–0.05%
Manganese (Mn)	0.01–0.05%
Zinc (Zn)	0.005–0.02%
Copper (Cu)	0.002–0.01%
Boron (B)	0.001–0.005%
Molybdenum (Mo)	0.0001–0.001%
Chlorine (Cl)	0.01–0.05%

Nutrient uptake and efficiency

Maize crop absorbs nutrients primarily through its root system (Wen-xuan et al., 2023), in the presence of different parameters such as pH and microbial activity (Sadeghi et al., 2023) and use of appropriate fertilisation practices (Al-Shammary et al., 2024). For instance, a pH of 6–7 avails most nutrients for maize while coarse-textured soils drain quickly but may not effectively hold nutrients. Poor soil structure encourages compaction, reduced root growth, and low nutrient uptake. Soil surfaces with more positive charges like K^+ can retain more nutrients. Healthy organic matter content encourages better nutrient

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cycling. Relatedly, soil microbes convert nutrients by breaking down organic matter into a more accessible form to plants.

Soil fertility management practices for maize crop

Soil fertility management is a critical aspect of sustainable agriculture, particularly for high-demand crops like maize (MacCarthy et al., 2023). As one of the world's most widely cultivated staple foods, maize requires optimal soil conditions and nutrient availability to achieve its full growth potential and maximise yields. Effective soil fertility management practices not only enhance nutrient supply but also improve soil structure, moisture retention, and overall ecosystem health (Al-Shammary et al., 2024). Implementing these practices contributes to robust maize production while promoting environmental sustainability and resilience in agricultural systems.

Soil testing

Soil testing is crucial for successful maize cultivation, providing valuable information on soil health, nutrient availability, and potential deficiencies (Batool, 2023). It involves collecting soil samples from various field locations, assessing both surface and subsoil conditions using tools like soil augers (Brunelle, 2020). These samples are analysed in a laboratory to measure key nutrients and pH, helping determine the nutrients available at different pH levels. Organic matter content is also evaluated to assess soil fertility and structure, which affect water retention and microbial activity important for maize growth (Zhang et al., 2022). The results indicate whether nutrient levels are sufficient, deficient, or excessive, and recommendations for lime (to raise pH) or sulphur (to lower pH) may be provided if the pH is outside the optimal range. Fertiliser application recommendations are made based on nutrient levels and pH to ensure maize receives the necessary nutrients for growth. Soil testing should be conducted every 2–3 years to monitor changes and adjust fertiliser types and amounts for efficient nutrient management (Beg et al., 2024).

Relevance of soil testing in maize production

Soil testing plays a crucial role in agriculture and environmental management by providing a comprehensive assessment of nutrient levels and deficiencies present in the soil (Fageria and Nascente, 2014). By analysing soil samples, farmers and land managers can identify specific nutrient imbalances that may hinder plant growth. This practice is essential for adjusting soil pH, ensuring optimal nutrient availability for crops. Furthermore, soil testing allows for the development of custom fertiliser recommendations tailored to the unique conditions of each site (Bhadu et al., 2022). By applying the right inputs based on accurate data, growers can enhance soil health, improve crop yields, and promote sustainable agricultural practices while minimising environmental impact.

Nutrient management in a maize crop field

Nutrient management is a crucial aspect of growing maize, ensuring that the crop receives the right balance of nutrients at the right times for optimal growth and yield (Bhat et al., 2024). It is essential to understand the specific needs of maize at its various growth stages, in certain soil types, and in different soil conditions (Yao et al., 2024).

Fertilisation strategies

This involves the use of organic (manure, compost) and inorganic (chemical fertilisers) sources to supply necessary nutrients. Nitrogen fertilisers such as urea, ammonium nitrate, calcium ammonium nitrate, urea ammonium nitrate, and other fertilisers should be applied based on soil tests. Phosphorus fertilisers such as superphosphate (single and triple), di-ammonium phosphate (DAP), and mono-ammonium phosphate (MAP) should be applied at planting time; while potassium fertilisers **(**Potassium chloride or potassium sulphate) can be used according to soil needs (Yan et al., 2022). Relatedly, the timing applications should be based on growth stages such as pre-planting, at planting, and during key growth phases (Nkebiwe et al., 2016). For example, side-dressing of nitrogen is done during the early vegetative stage of the crop. Another strategy is fertiliser placement such as banding or broadcasting to manage nutrient availability and uptake efficiency (Wang et al., 2024). In accordance with soil fertility, expected yield, previous crop history, and rainfall conditions, the recommended application rate for nitrogen fertilisers is 120–200 kilogrammes per hectare (kg ha^{-1}); phosphorus (P) fertilisers 60–80 kg ha^{-1} (low P soils), 30–50 kg ha^{-1} (moderate P soils), and 20–30 kg ha^{-1} (high P soils – requiring maintenance dose); and potassium (K) fertilisers 100–150 kg ha^{-1} (low K soils), 60–100 kg ha^{-1} (moderate K soils), and 40–60 kg ha^{-1} (high K soils – requiring maintenance dose) (Nutrient management guidelines for some major field crops – Food and Agricultural Organisation, 1999).

Nutrient efficiency practices

In Precision Agriculture, the practices include utilising technology, such as soil sensors and GPS, to apply nutrients more precisely based on specific field conditions (Getahun et al., 2024). Another efficient practice is split application which involves dividing fertiliser applications into multiple doses to improve nutrient uptake and reduce leaching or runoff (Belete et al., 2018). Splitting the fertiliser doses applies where the targeted nutrient is highly mobile in the soil. For instance, a farmer may apply the required 100% nitrogen into two: at planting (30–40%) and during growth (6–8 leaves) or at the beginning of tasseling (60–70%). Incorporating manure, such as compost, can increase soil organic matter, improve nutrient availability, and enhance soil structure (Goldan et al., 2023). Monitoring and adjustment of nutrient efficiency is vital and can be done by regular visual assessment of plant health and growth to identify nutrient deficiencies or excesses; and adjusting

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practices based on observations and soil test results (Islam et al., 2023). Nutrient management practices should be adjusted for future planting seasons of the maize crop.

Soil pH management in a maize crop field

Soil pH is a critical factor that influences nutrient availability and overall soil health, particularly in maize cultivation (Barrow and Hartemink, 2023). Acidic soils can limit nutrient availability and increase aluminum toxicity, while slightly acidic to neutral soils (pH 6.0 to 7.5) optimise the availability of nitrogen, phosphorus, and potassium (Al-Shammary et al., 2024). Understanding soil pH is vital for effective maize management, as it impacts microbial activity and crop growth (Bhat et al., 2024). Regular soil pH testing helps farmers determine whether the soil is suitable for maize, revealing nutrient deficiencies or toxicities at extreme pH levels. Laboratory tests provide precise results, including details on nutrient levels and soil texture, while DIY pH kits offer a quick, cost-effective way to assess soil on-site (Faria et al., 2023).

To raise soil pH in acidic soils, lime (calcium carbonate) is commonly applied, improving nutrient availability and microbial activity (Wakwoya et al., 2022). Lime should be applied several months before planting for effective soil reaction. For alkaline soils, sulphate fertilisers can lower pH to make nutrients more available (ulShahid et al., 2023). Regular nutrient assessments help adjust fertilisation strategies to ensure optimal nutrient availability for maize (Al-Shammary et al., 2024). Additionally, crop rotation and proper post-harvest residue management improve soil health (Zong et al., 2024). Cover crops planted during the off-season can also help maintain soil pH and structure (Koudahe et al., 2022).

Water management in a maize crop field

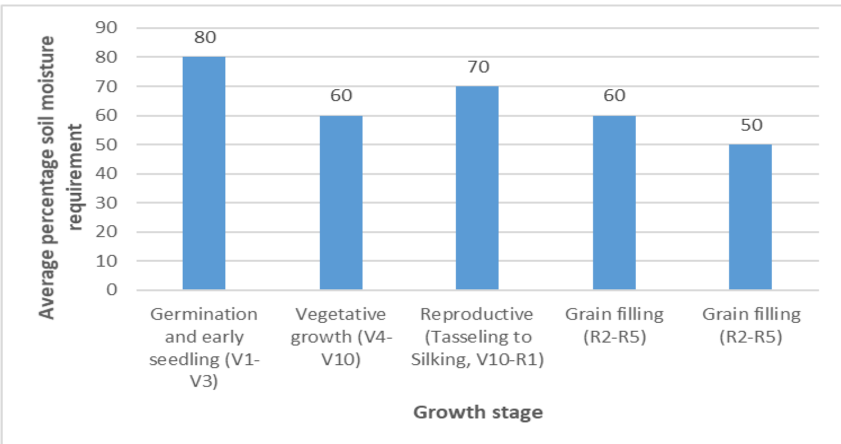
Water management is a critical aspect of maize cultivation, as adequate moisture is essential for seed germination, nutrient uptake, and overall crop health. In circumstances when rainfall is unpredictable, bed ridges can be lined with organic mulches (*Figure 2*). Effective water management practices help optimise water use efficiency, enhance yields, and promote sustainable agricultural practices (Lamlom et al., 2024).

Figure 2. **Water management in a maize field (Uwizeyimana et al., 2018)**

Source: Sciencedirect.com

In the growing of maize, water management involves understanding the water requirements. According to *Figure 3*, maize requires significant water during various growth stages, particularly during germination, flowering, and grain filling (Kebede et al., 2014; Șimon et al., 2023). This implies that the average moisture requirement at different growth stages of a maize crop is expressed as percentage of the soil's field capacity.

Figure 3. **Average soil moisture requirements by growth stage for maize**



Monitoring evapotranspiration using high-resolution UAV-based imagery helps determine water needs based on local climate and growth stages (Cheng et al., 2023). Regular soil moisture checks with probes, tensiometers, or moisture sensors assess whether the soil is too dry or adequately moist. Understanding field capacity, or the amount of water soil can hold after excess drains, is crucial for irrigation scheduling (Zhang et al., 2024). The appropriate irrigation method, such as flooding, furrow, drip, or sprinkler systems,

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depends on resources, climate, and field conditions (Liu et al., 2018). Irrigation is scheduled based on growth stages and soil moisture to ensure water is applied when maize needs it most (Datta et al., 2017).

Water conservation techniques are practices aimed at reducing water use and enhancing water efficiency. These methods can include strategies like rainwater harvesting, drip irrigation, mulching, and using drought-resistant plant varieties (Xing and Wang, 2024). Implementing these techniques in maize growing helps to minimise water waste, protect natural water resources, and ensure sustainable water supply for agriculture and other uses. By promoting responsible water management, these practices contribute to environmental health and resilience against droughts (Lebu et al., 2024).

Drainage management in a maize crop field

Drainage management is crucial for maize cultivation as it affects soil health, root development, and crop productivity. Proper drainage prevents waterlogging and excess moisture, which can damage maize roots and reduce yields (Huang et al., 2022). Soil texture and structure must be assessed since different soils have varying drainage capacities–sandy soils drain quickly, while clay soils retain water (Prajisha et al., 2023). Field slope and elevation should be evaluated to understand natural water movement and potential pooling areas (Xu et al., 2021). The maize field should be designed with proper slopes to facilitate drainage, possibly including channels or ridges. Ditches, trenches, or drains may be added to manage excess water in specific areas (Koomson et al., 2020). Regular inspections of drainage systems are necessary to ensure they function properly, without blockages or sediment buildup (Arumugam et al., 2019).

Fertiliser types and application methods for maize

Fertiliser types for maize

The successful cultivation of maize relies on understanding and managing soil fertility, which is essential for achieving optimal growth and maximising yields (Boansi et al., 2024). The nutrient requirements of maize are substantial, demanding a careful balance of macro-nutrients and various micro-nutrients (ten Berge et al., 2019). To meet these nutrient requirements, farmers have access to a wide array of fertilisers, each with unique properties and benefits. Fertilisers applied to a maize crop are clearly categorised as nitrogen fertilisers such as CAN; phosphorus fertilisers such as DAP; potassium fertilisers such as Muriate of potash (KCl); and secondary nutrients and micronutrients such as gypsum and Chelated micronutrients (Zn, Fe, Mn, etc). The choice of fertiliser type, along with the method of application, plays a crucial role in nutrient availability and uptake by plants (Barłóg et al., 2022).

Fertiliser application methods

Fertiliser application methods are critical in maximising the efficiency of nutrient use in agriculture, particularly for edible crops like maize. The way fertilisers are applied can significantly influence their availability to plants, the potential for nutrient loss, and overall crop yield (Shanmugavel et al., 2023). The effectiveness of nutrients depends not only on their formulation but also on how and when they are applied (Kumari et al., 2022). Different methods can enhance or inhibit nutrient uptake, affect soil health, and influence the environmental impact of agricultural practices (Al-Shammary et al., 2024).

Broadcasting involves spreading fertilisers evenly over the soil surface before or after planting. It is a quick, simple method suited for large fields and various soil types, improving nutrient distribution. However, it risks nutrient runoff, especially for water-soluble fertilisers, and may lead to inefficient nutrient uptake, particularly for phosphorus and potassium. To improve efficiency, fertilisers should be incorporated into the soil, and broadcasting should be combined with tillage practices (Raniro et al., 2023). The banding method places fertilisers in concentrated bands at specific depths near the seed row during planting. It reduces nutrient loss and enhances nutrient availability, especially for phosphorus. However, it requires precise equipment, increasing costs, and may be less effective in poorly drained soils (Alam et al., 2018). Banding should be timed to match crop needs and growth stages. Side-dressing applies fertilisers alongside growing crops, targeting nutrient needs at key growth stages. It reduces competition with seedlings, especially for nitrogen (Amali and Namo, 2015). However, it increases labor and equipment costs, and timing is crucial. Foliar application involves spraying liquid fertilisers onto plant leaves, providing a quick nutrient boost, especially for micronutrients (Nadeem and Farooq, 2019). It is a supplement to soil fertilisation but cannot fully replace it. Best practices include applying during cooler parts of the day and ensuring thorough coverage. Fertigation combines fertilisers with irrigation, delivering nutrients directly to the root zone (Quemada and Gabriel, 2016). It offers precise control but requires investment in infrastructure. Deep placement places fertilisers at greater soil depths, reducing runoff and targeting deeper roots (Wu et al., 2022). However, it requires specialised equipment and may increase costs, making it suitable for soils prone to nutrient leaching (Huang et al., 2024).

Impact of soil nutrient management on maize yield and quality

Soil nutrient management is crucial for maize production, affecting both yield and quality (Bhat et al., 2024). Proper nutrient management, including fertilizers and organic amendments, boosts soil fertility, supports healthy growth, and optimizes resource use. Deficiencies in key nutrients like nitrogen, phosphorus, and potassium can stunt growth, reduce kernel formation, and increase vulnerability to pests and diseases. On the other hand, effective nutrient management enhances maize resilience to environmental stresses, leading to better yields and grain quality (Hasanain et al., 2024). Overall, soil nutrient management is vital for increasing

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productivity, improving grain quality, and ensuring food security and economic viability (Kurbah, 2016).

Impact of nutrient management on maize yield

Maize productivity heavily relies on effective nutrient management, which includes fertiliser application, organic amendments, and agronomic practices that improve soil fertility (Dawar et al., 2022). Proper nutrient supply, tailored to maize's growth cycle, enhances growth and yield. Inadequate or unbalanced nutrient use can result in reduced yields, poor grain quality, and increased pest and disease susceptibility (Aliyu et al., 2021). Optimising nitrogen, phosphorus, and potassium applications can significantly increase yields, as seen with nitrogen boosting ear size and kernel count. Fertiliser applications based on soil tests and crop needs can boost yields by 20–30% (Singh et al., 2021). Regular soil testing helps identify nutrient deficiencies and pH imbalances, enabling targeted nutrient applications. Additionally, practices like conservation tillage and adding organic matter improve soil health, enhancing moisture and nutrient retention, which is crucial for maize production (Mhlanga et al., 2022).

Environmental considerations

While effective nutrient management is crucial for maximising maize yield, it is also important to minimise environmental impacts. Nutrient runoff is a concern accelerated by over-application of fertilisers. Sustainable practices, such as precision agriculture, can help mitigate this risk by ensuring precise applications (Mgendi, 2024).

Impact of nutrient management on maize quality

Effective nutrient management is critical in determining these quality attributes, as it directly impacts the physiological processes within the plant (Noulas et al., 2023). The grain quality of maize is crucial for human consumption, livestock feed, and industrial use (Erenstein et al., 2022).

Grain quality in maize is influenced by several factors, including kernel size, weight, nutritional content, and resistance to pests and diseases (Kumar et al., 2019). Adequate phosphorus and potassium levels are crucial for developing kernels rich in starch and protein and these can be increased by protein nutrient management. Optimal nutrient levels contribute to larger, heavier kernels, which are more desirable for both human consumption and animal feed (Jiaying et al., 2022).

Technological advances in soil and nutrient management

Soil variability monitoring

Recent advancements in remote sensing and precision agriculture offer innovative methods for monitoring soil properties that are of importance to maize growing (Zhang et al., 2024). This is in addition to soil tests and Geographical Information Systems (GIS).

Soil tests

Routine soil testing provides baseline data on nutrient levels, pH, and organic matter content (Fageria and Nascente, 2014). Tests can be conducted using soil cores collected from various field locations to assess spatial variability. Results inform targeted interventions, such as variable-rate fertilisation of the maize crop (Guerrero & Mouazen, 2021).

Remote sensing technologies

These include: Satellite imagery, where high-resolution satellite imagery can be used to assess vegetation health, soil moisture, and organic matter indirectly through indicators like Normalised Difference Vegetation Index (NDVI) (Fadl et al., 2024) (*Figure 4*). This data helps identify areas, including those covered by the maize crop, that need attention. Drones equipped with multispectral cameras (*Figure 5*) can also be used to capture detailed imagery at a lower cost (Louw et al., 2024). They allow for real-time monitoring of maize crop health and soil conditions, facilitating timely interventions.

Figure 4. **Remote sensing of soil in a maize field (Buthelezi et al., 2023)**

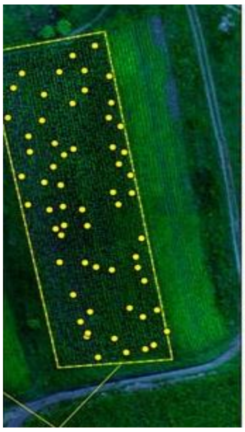

Figure 5. **Drone equipped with multispectral camera (Peña-Barragán et al., 2014)**

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Besides, soil moisture sensors are installed in the field to provide continuous data on moisture levels, enabling precise irrigation management. Sensors can be combined with remote sensing data for comprehensive monitoring of the maize crop (Toureiro et al., 2016). Geographic Information Systems (GIS) and Spatial Analysis are also used to integrate soil test results with remote sensing data to create detailed soil maps (Abdulraheem, 2023). These maps illustrate variability across a maize field, allowing for informed decision-making regarding fertilisation, irrigation, and the crop management practices (Maynard et al., 2023).

CONCLUSIONS

Soil properties play a crucial role in maize (Zea mays) production, with biological, chemical, and physical characteristics influencing nutrient availability and water retention. Loamy soils, with balanced sand, silt, and clay content, are ideal for maize, offering good drainage and moisture retention. Regular soil testing and monitoring help identify deficiencies, optimise fertilisation, and guide sustainable farming practices. Future research should focus on developing advanced, quicker soil testing methods, particularly in variable soil regions, and exploring the relationship between soil microbial activity and maize productivity. Additionally, integrating technologies like remote sensing, GIS, and soil moisture sensors can improve precision farming. Machine learning and big data analytics could enhance predictions of soil variability and crop performance. Lastly, evaluating the long-term impacts of precision agriculture tools on soil health and productivity, and examining the economic and environmental benefits for small-scale farmers, will provide insights into the sustainability and scalability of these technologies.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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