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Review

Enhancing Maize Production Through Timely Nutrient Supply: The Role of Foliar Fertiliser Application

Brian Ssemugenze [1,2], Akasairi Ocwa [1,2], Ronald Kuunya [1,2], Costa Gumisiriya [2,3,4], Csaba Bojtor [1,*], János Nagy [1], Adrienn Széles [1] and Árpád Illés [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] Institute of Agrochemistry and Soil Science, Faculty of Agricultural and Food Sciences and Environmental Management, University of Debrecen, 138 Böszörményi Street, 4032 Debrecen, Hungary
[4] Department of Crop and Animal Production, Faculty of Agriculture and Environmental Sciences, Mountains of the Moon University, Fort Portal City P.O. Box 837, Uganda
* Correspondence: bojtor.csaba@agr.unideb.hu

Abstract: Maize, regarded as a staple economic crop, attracts special global attention with the aim to enhance its production. Foliar fertilisation offers a complementary method to traditional soil fertilisation amongst resource-limited agricultural systems, providing a more efficient solution to nutrient deficiencies, especially in suboptimal soil conditions. This study aimed to analyse foliar fertiliser formulation research directions and their application in maize production. A literature search was conducted in the Web of Science (WoS) database. Bibliometric analyses were performed using the VOSviewer software (version 1.6.17). The changes in the publication trends of documents were tested using the Mann–Kendall test. The production effects of foliar fertilisation were independently synthesised. The results showed a strong positive increase in publication trends regarding maize foliar fertilisation (R^2 = 0.7842). The predominant nutrients that affected maize production were nitrogen, phosphorous, potassium, zinc, iron, and manganese. The timely foliar application of nutrients corrected deficiencies and/or sustained nutrient supply under several abiotic stresses. Foliar application at critical growth stages like flowering and grain filling boosted carbohydrate and protein content, lipid levels, kernel size, mineral content, and the weight of the maize grain. This review identified important research gaps, namely genotype-specific responses, interactions with other agronomic practices, and long-term environmental effects.

Keywords: foliar application; fertiliser; maize; production

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1. Introduction

Maize is among the leading cereal crops widely grown and consumed globally. In fact, maize, together with rice and wheat, are the global staple cereals that account for close to 42% of the world's food calorie intake [1,2]. The current data in the FAO database show that as of the year 2022, the global maize production was 1.16 billion tonnes compared to 1.21 metric tonnes in 2021. In terms of the regional share of maize production, 49.6% was from the United States of America, 33.5% was from Asia, 8.8% was from Europe, 8.0% was from Africa, and 0.1% was from Oceania (https://www.fao.org/faostat/en/#data, accessed on 18 December 2024). Regarding utilisation, 56% of the maize produced is predominantly used as feed, 13% is used for food, and one fifth of the total produced is used for non-food uses [1,3]. According to the FAO [4], the increasing consumption of meat and the rising need for biofuels is commensurate with the growing demand for maize, and this demand is expected to continue increasing and place more pressure on agricultural systems. Owing to the benefits of maize, maintaining optimum maize production becomes of key importance. Although the global average maize yield has been changing every year, it remains superior to the rest of the cereals produced in the same time period. Generally, sustaining a high yield of maize and other crops requires fertile arable land and plant fertilisation [5,6], nutrition and nitrogen application [7,8], irrigation and water supply [6,7], favourable weather and climatic conditions [9,10], the judicious use of agrotechnical inputs, and continuous research to develop new innovations [11]. Foliar fertilisation is another approach that is gaining increasing attention as nutrients are directly applied to the leaves of the plant, allowing for immediate nutrient uptake and potentially addressing nutrient deficiencies during critical growth stages of the maize crop compared to traditional soil-based fertilisation.

Foliar fertilisation, a method that involves the direct application of liquid fertiliser to plant leaves [12], serves as a significant tool for the sustainable and productive management of crops [13]. This precision practice is crucial in mitigating the impact of abiotic and biotic stresses on crop growth and yield. Foliar fertilisers not only provide essential nutrients but also alleviate stress factors and enhance the chlorophyll content, the photosynthetic rate, and resistance to pests and diseases [14]. By reducing lipid peroxidation and maintaining homeostasis, foliar fertilisation proves effective in improving the yield and grain quality of crops like maize (*Zea mays* L.) under stress conditions [15,16]. Supplying nutrients at precise times and quantities is crucial for optimal plant growth. Foliar application, which delivers nutrients precisely when plants need them, minimises the time between application and absorption [17,18]. Foliar fertilisation alleviates nutrient supply challenges encountered when using soil fertiliser application, such as fixation [19] and inadequate moisture in the top soil that is essential for nutrient absorption by plant roots [19,20]. In fact, the efficacy of foliar fertilisation is higher than that of soil fertiliser application under drought conditions [20,21]. However, the foliar fertiliser method has some limitations, such as a scorching effect under high concentrations [22], the prohibitive cost of multiple applications [21], and an efficiency dependent on climatic conditions [12].

Several studies have explored the impacts of foliar fertilisation on various aspects of maize growth, including yield, nutrient content, photosynthetic efficiency, and resistance to environmental stressors. When applied during the grain initiation stage, foliar spraying provides the essential nutrients required to achieve an optimal number of grains per plant [11,23]. Nano-sized foliar fertilisers offer rapid nutrient replenishment for nutrient-deficient plants, especially in challenging conditions, supplying elements that are challenging to absorb through roots [24,25]. Nutrients delivered through foliar application are swiftly absorbed and assimilated with studies indicating that 100% of nitrogen (supplied as a urea fertiliser) can be absorbed by plant leaves in approximately four hours [12]. The direct foliar application of phosphorus enhances phosphorus use efficiency and concentration in grains [26,27]. Numerous reports have demonstrated that foliar fertilisation enhances nutrient absorption and utilisation, leading to maximum grain yields in crops [20,28]. However, these results vary depending on factors such as nutrient formulation, application timing, and environmental conditions.

Additionally, the application of nutrients, such as phosphorus, improves fertiliser use efficiency as a result of this technique [29,30]. Rácz et al. [31] observed the positive effects of foliar fertilisation in yield components, such as 1000 kernel weight, ear diameter and length, the number of rows per ear, and grains per row. Reports also indicate slightly increased starch and protein content, except for oil content, following the application of foliar fertilisers [31,32]. Generally, nutrients applied to the foliage are absorbed more rapidly than those applied to the soil, although the earlier is mainly used for nutrient replenishment. Therefore, a review was conducted to analyse the research directions of foliar fertiliser formulations as well as their application in maize production.

2. Materials and Methods

2.1. Database Identification and Literature Search

This review is focused on documents retrieved from the Web of Science database, as it is one of oldest databases and contains the related research publications. Web of Science is a user-friendly database which contains peer reviewed articles and makes a literature review easier as well as data visualisation using various software, such as VOSviewer [33] archiving high-quality literature. This study was conducted in several stages. The first step was a general search for available scientific literature on maize production through foliar fertilisation (MPFF) in the WoS database. The literature research was performed between August and September 2024. The search keywords were ((“Maize” OR “Corn”) + “Foliar” + (“Fertilisation” OR “Application”) + “Production”) restricted by topic including title, abstract and keywords for the period 2014–2024. This step retrieved 357 documents. As a next step, the search was restricted to only English, which yielded a total of 341 documents. After a careful screening by keywords, abstract and title based on the occurrence of keywords mentioned above and their relevance to the objective of the study, a total of 157 documented were retrieved. These 157 documents were included for literature trend analysis and keyword network analysis. The purpose of the full article review of these 157 documents was to be able to synthesise the effects on foliar fertiliser on maize production parameters. It is worth noting that during the full article review, the evidence of the foliar fertiliser effect on growth parameters as well as yield and seed quality attributes was the main focus. In accordance, even if the article had all necessary keywords but no evidence of any effect on maize production, or it had all keywords with evidence of the effect of foliar fertiliser application on other crops, it was excluded. This method ensured that only relevant articles were included for the section of network analysis after a full review for general production effect synthesis (Figure 1).

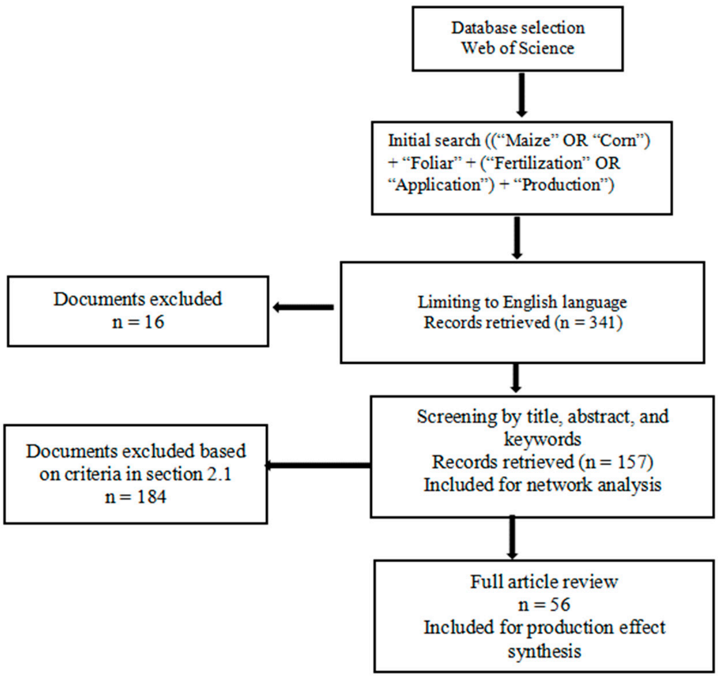

Figure 1. PRISMA showing literature search and screening process.

2.2. Data Exportation and Analysis

The metadata of the 157 documents were exported as a CSV file from the Web of Science database. After conversion to Microsoft Excel format, the publication trend was analysed using the Mann–Kendall Test with EVIEWS software (12 version). Bibliometric analyses were carried out using the VOSviewer bibliometric tool [34]. Key units of analysis in the bibliometric synthesis included different types of foliar fertilisers and the co-occurrence of foliar fertiliser effects on maize growth, grain yield and quality (based on author keywords and all keywords). The link strength and co-occurrence of keywords was the basis for network analysis interpretation. Also, effects from differently foliar fertilisers were independently synthesised.

3. Results and Discussion

3.1. Trend of Included Literature

The Mann–Kendall test value of 0.7842 (Figure 2) shows a strong positive trend regarding the number of research publications on the foliar fertilisation of maize. The trend analysis indicates that the application of foliar fertilisers to improve maize production was an interesting topic for various researchers. The breakdown of the research publication trend indicates that between 2014 and 2018, the number of publications ranged between 3 and 7 articles; however, this tendency significantly increased between 2019 and 2024, ranging from 10 to 25 articles (Figure 2). This positive trend indicates a growing research interest focused on foliar fertiliser applications in maize production, which directly correlates with an increased demand for improved agricultural productivity and food security [35,36], increased agricultural investment and innovation [37,38], solving agricultural challenges through sustainable agriculture aimed at resolving maize nutrient deficiencies [10,39]. Since maize is a global staple crop [4], the application of precision production methods such as foliar fertilisation is critical. Therefore, an upward publication trend suggests an increased validation of foliar fertilisation by scientific studies toward boosting maize yields and quality, improved nutrient uptake efficiency, and contribution to sustainable agriculture. The increasing trend in publications on foliar fertilisation indicates its growing relevance in addressing agricultural policy and technological advancements. Foliar fertilisation aligns with policies promoting sustainable agriculture by enhancing nutrient use efficiency and reducing environmental impacts [40]. Technological innovations, such as precision agriculture and advanced formulations, have improved the effectiveness of foliar applications, making them attractive alternatives to traditional soil fertilisation [41]. Additionally, the global emphasis on mitigating climate change has driven research on sustainable fertilisation methods [42]. This trend indicates the intersection of policy priorities and technological progress in modern agriculture.

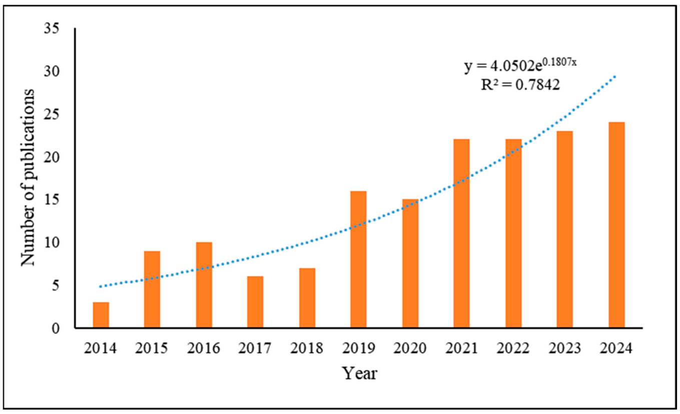

Figure 2. Research publication trend analysis between 2014 and 2024.

3.2. Network Analysis of Included Literature

The predominant investigated areas of foliar fertiliser application in maize production based on overall occurrence and the total links of all author keywords are summarised in Table 1. In terms of co-occurrence, the key areas investigated were yield, plant growth, abiotic stress tolerance, nitrogen uptake and use efficiency, soil, photosynthesis or photosynthetic rate, productivity, nutrient uptake or use efficiency, micronutrients, zinc or ZNO or zinc foliar application, biofortification, iron and deficiency corrections with the occurrence of 65, 51, 34, 24, 17, 16, 13, 11, 10, 10, 9, 8 and 8, respectively. In accordance, the associated total link strength of the above keywords was high. Specifically, the analysis of the total linkage of all author keywords and specific author keywords revealed several insights (Figures 3 and 4). For example, the foliar application of nitrogen was linked with the increase in chlorophyll content, and nitrogen use efficiency, which is correlated with grain yield improvement. In addition, foliar application was strongly linked with zinc, boron, manganese, and protein improvement in maize. In other words, foliar fertiliser application in maize enhanced biofortification. In addition, in circumstances such as salinity, and other soil conditions that showed limited nutrient absorption by maize as a result of climate change, foliar fertiliser appeared to be an appropriate solution based on the analysed linkages. Also, there was a strong linkage of phosphorus availability, iron and zinc bioavailability with soil application, which also had a link with foliar fertiliser application. The author KeyWords Plus (Figure 5) shows that in addition to the supply of the essential elements, the foliar supply of amino acids was linked to the tolerance of maize genotypes to abiotic stress factors, especially drought and salinity. In the linkage analysis of all keywords, foliar nutrient application was directly or indirectly linked with soil application, depicting the relevance of balanced nutrient application in the case of both strategies. Generally, the predominant foliar-supplied essential macronutrients and micronutrients were nitrogen, potassium, and zinc, respectively. Several studies conform the role of foliar fertilisation in improving maize productivity. Foliar feeding enhances quick nutrient supply and consequent correction of deficiencies while meeting the specific requirements of a crop [12]. Earlier, maize productivity was reported to be high under foliar potassium supply compared with soil and other application methods [43] and under extreme drought conditions [44]. Similarly, zinc foliar nutrition was reported to enhance enzymatic antioxidant and physiological plant defence mechanisms, hence improving resistance to abiotic stress hastened by climate change [45].

Table 1. Overview of the predominant investigated areas of foliar fertiliser application in maize production based on overall occurrence and total links of all author keywords.

Keyword(s)	Co-Occurrence	Total Link Strength
Yield or grain yield	65	300
Yield components	3	12
Growth or plant growth	51	223
Abiotic tolerance	34	149
Nitrogen or nitrogen use efficiency or nitrogen uptake	24	96
Photosynthesis or photosynthetic rate	16	76
Soil	17	92
Biofortification	9	58
Productivity	13	54
Iron	8	50
Deficiency	8	47
Micronutrients	10	51

Table 1. *Cont.*

Keyword(s)	Co-Occurrence	Total Link Strength
Water relations	7	36
Salinity	7	32
Humic-acid	8	47
Nutrient use efficiency or nutrient-uptake	11	50
Phosphorus OR Phosphates	7	45
Zinc or ZNO or zinc foliar application	10	61
Chlorophyll content	4	18
Potassium	3	17
Amino-acids	3	13
Magnesium	3	12
Toxicity	2	10
Climate change	2	4
Biofertilisers	3	12
Protein content	2	12
Manganese	2	12

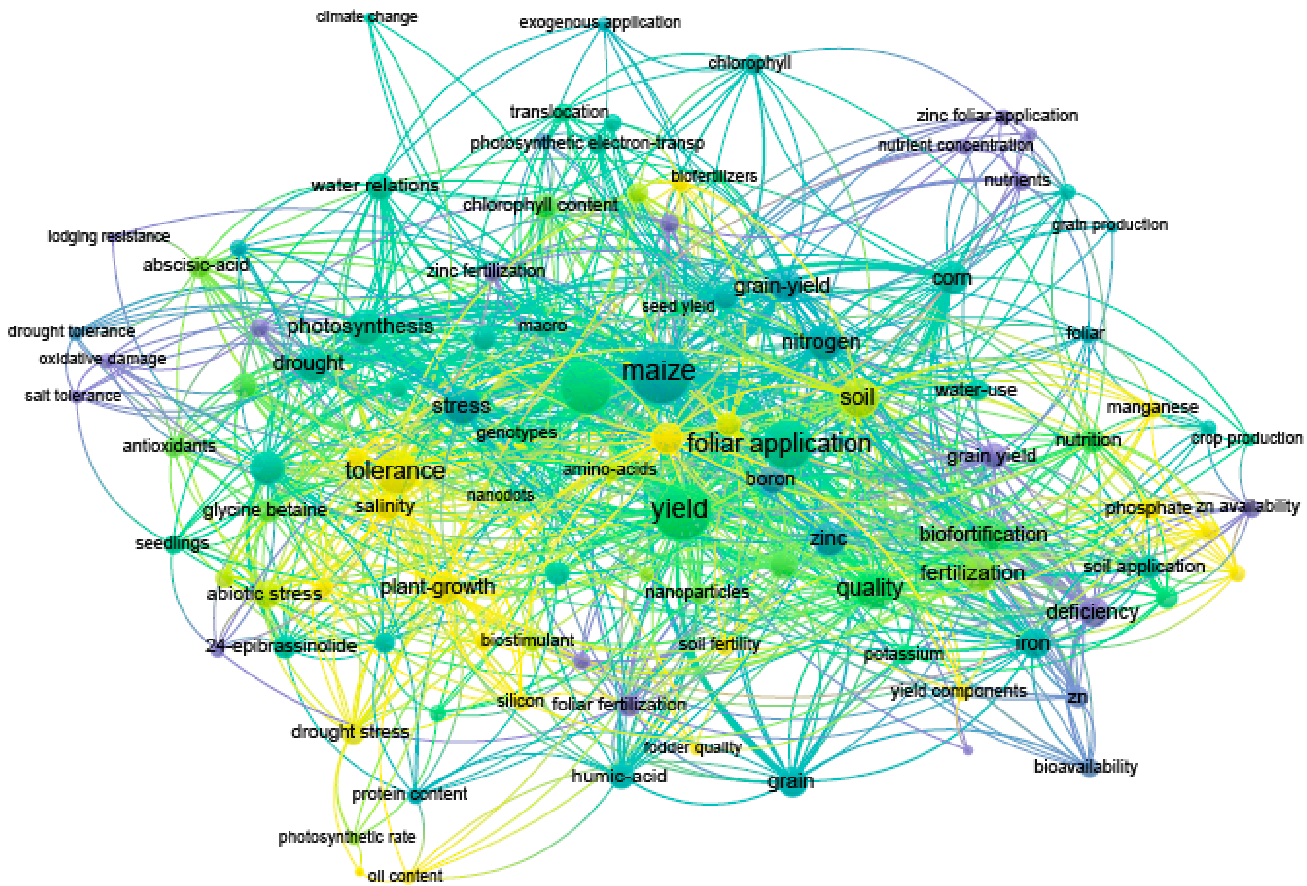

Figure 3. Total linkage of all-author keywords depicting predominant investigations of foliar fertiliser application in maize production.

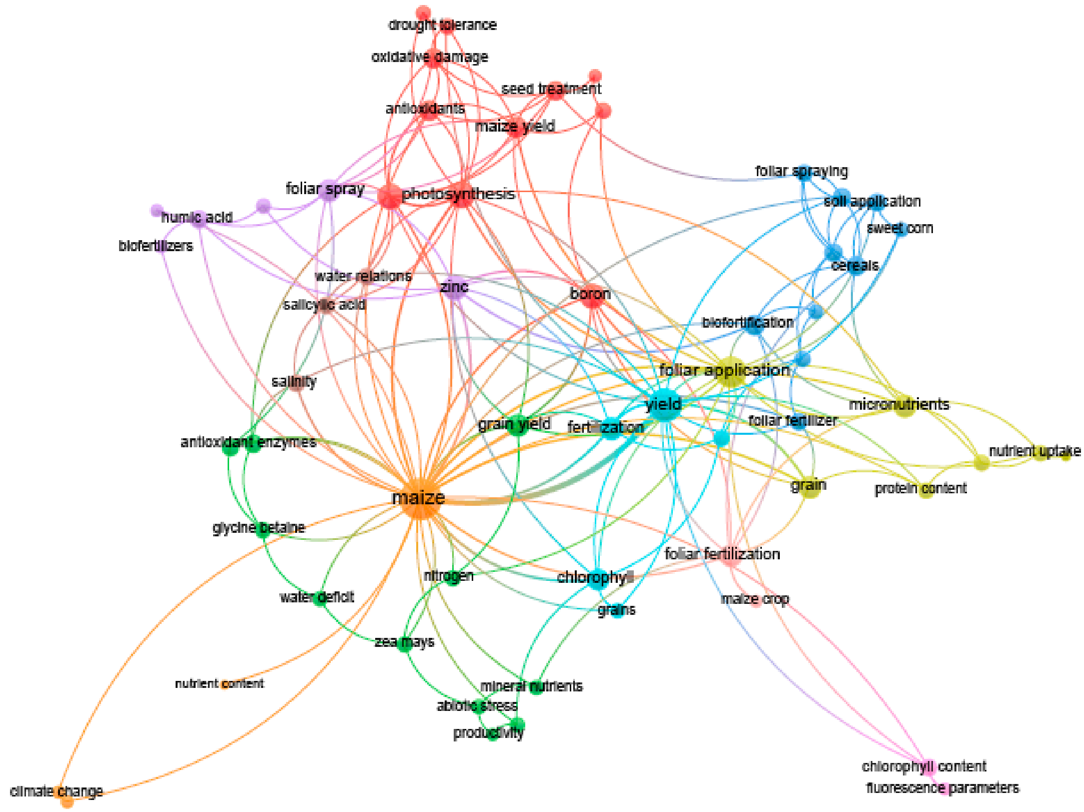

Figure 4. Total linkage of specific author keywords depicting predominant investigations of foliar fertiliser application in maize production.

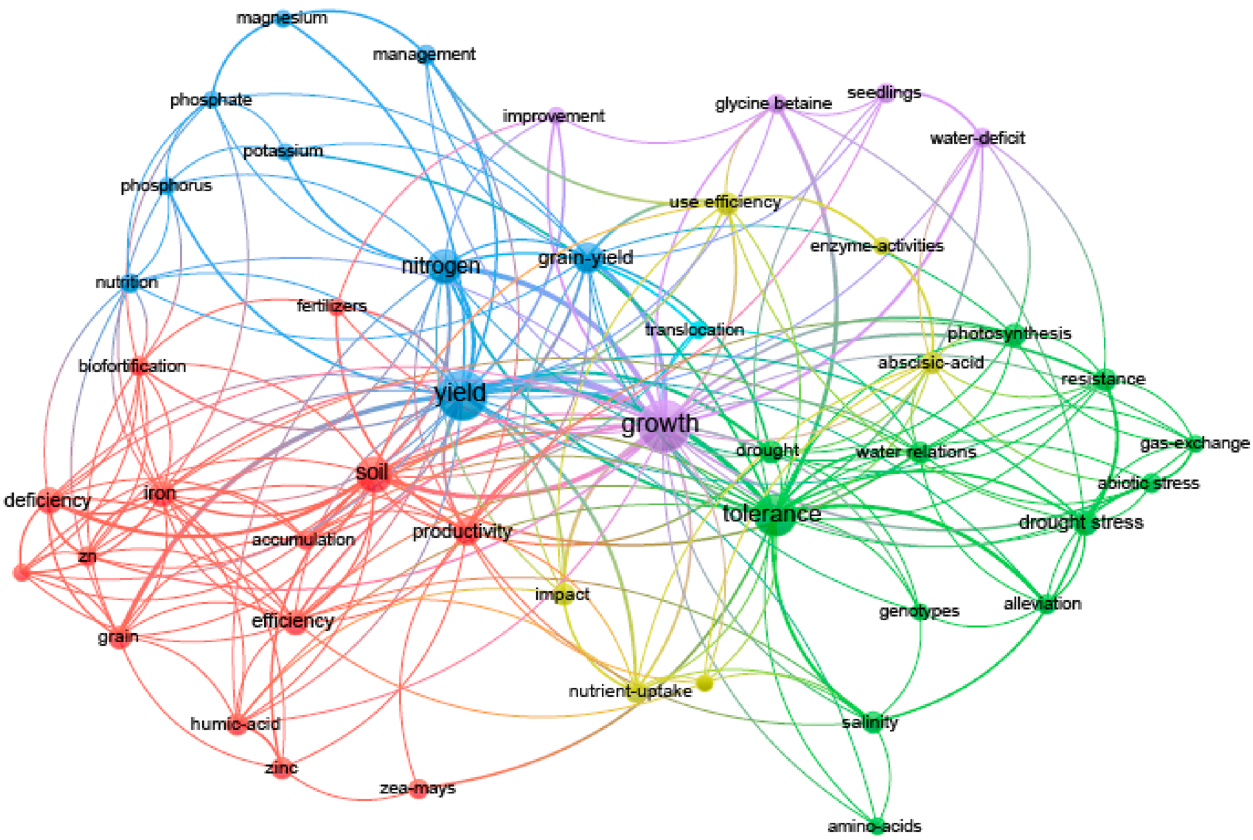

Figure 5. Total linkage of KeyWords Plus depicting predominant investigations of foliar fertiliser application in maize production.

3.3. Different Foliar Fertilisers and Mineral Nutrients Applied to Maize

Several studies indicated different foliar fertilisers including both organic and inorganic compounds. In nitrogen-based foliar fertilisers, nitrogen is essential for maize growth, development and chlorophyll synthesis. Younis Al-Ghazal et al. [46] applied a biofertiliser containing *Trichoderna viride*, *Azospirillium*, *Bacillus* spp., *Azotobacter*, *Pseudomonas fluorescens* and *Lactobacilli* with nitrogen (2.3%), carbon (16.1%), and organic matter (32.2%) on maize plants and noticed improvements within 21 days after planting. Upadhyay et al. [47] also studied a maize management approach using two nano-fertilisers, namely N75PK+nano-N and N75PK + nano-N + nano-Zn) to increase yield. Different urea concentration levels (0.10–3.20%) were applied for summer maize at V6, V12, VT and R2, recommending that urea concentration doses of 0.40%, 0.25–0.40%, 0.10–0.80%, and 0.25–0.40% maximized the relative chlorophyll content and photosynthetic capacity [48]. Biswal et al. [49] studied different Ortho Silicic Acid (OSA) concentrations (0.05%, 0.10%, 0.15%, 0.20%, 0.25%, and 0.30%) applied at 30 days after the seedling (DAS) stage, together with the recommended fertiliser dosage. Buligon et al. [50] studied how a liquid biofertiliser (digestate obtained from swine wastewater anaerobic digestion) acts as the total or partial substitution of synthetic nitrogen fertiliser. Furthermore, it is advisable to apply foliar nano-chitosan-loaded N (CS-NNPs) for improved efficacy and production [51]. Therefore, nitrogenous foliar fertilisers were applied in different forms such as urea or ammonium nitrate, nano-chitosan-loaded N, biofertilisers such as Bactovid, Ortho Silicic Acid (OSA), digestate to improve maize growth and yield when sprayed at the critical growth stages of maize growth.

Although phosphorus and potassium foliar fertilisers are well known for root development, energy transfer, water regulation and disease resistance, respectively, the foliar application of both minerals is less pronounced compared to nitrogen. However, this study has reviewed important research results. An organic solution obtained from calcinated bones was sprayed onto maize plants grown on phosphorous-deficient soils to reclaim phosphorous in [52], and a foliar application of different concentration levels of mono-ammonium phosphate (0.03–4.80%) and potassium sulphate (0.10–4.80%) at V6, V12, VT and R2 growth stages of summer maize benefited plant growth [30]. Nano-potassium applied together with humic acid at rates of 500 cm^3ha^{-1} and 10 ton ha^{-1} improved the physiological growth, yield and quality parameters of maize [53]. Gorlach and Muhling [54] noted that phosphorous foliar application can be an important top-up treatment in deficiency circumstances.

Other micronutrient foliar fertilisers, mainly different micronutrients, have been studied due to their role on maize production improvement. A nano-active foliar biostimulant called Kelpak, containing auxins, cytokines, CaO and other different nutrients such as Zn, Fe, Mg, and Mn [55] was applied to improve maize yield. The application of natural Zn ($ZnSO_4$) on old maize leaves significantly increased Zn concentration [56]; therefore, foliar zinc application rejuvenates old plant leaves, thus enhancing chlorophyll content. The foliar application of different zinc forms such as ZnO, ZnONP, $ZnSO_4$ and ZnEDTA improved various maize plant growth parameters under drought conditions [57,58], which is an implication that foliar micronutrient application performs well under different stresses such as drought. The application of different silicon sources such as nano-silica (Nano), sorbitol-stabilised sodium + potassium silicate (SiAl), potassium silicate without stabilisers (SiK) and PEG-400-stabilised mono-silicic acid (SiAc) enhances maize production mainly if leaf silicon contents are lower [59]. The foliar application of Amino Ultra Kukurydza or Plonvit Kukurydza coupled with Bacillus improved maize grain yield per ear, protein content, zinc and iron grain content [60]. The foliar application of micronutrients such as zinc, silicon, copper, sodium, Fe, Mg, and Mn has been reported to improve maize growth, grain quality, yield, and biomass, chlorophyll production and overall maize plant health.

3.4. Effect of Foliar Fertiliser Application on Maize Growth, Grain Yield and Quality

3.4.1. Physiological Growth

The foliar application of fertilisers greatly influenced the growth and physiology of maize at different stages. The foliar zinc application at 100 mg Zn l^{-1} rate influenced plant height, leaf area index, ear grain number, and 500 grain weight [61] when zinc was applied on maize in the form of ZnEDTA and $ZnSO_4$, together with trehalose, influencing chlorophyll content and fluorescence, root electrical capacity, and aboveground biomass weight (AGB) according to [57]. Notably, Al-Ghazal et al. [46] recorded a positive effect on growth parameters due to the application of biofertilisers extracted from seaweed with the exceptions being the number of cobs, stem diameter and plant height during different seasons. OSA, a different biofertiliser, was applied at a concentration of 0.25%, positively influencing maize growth and physiological indices, including crop growth rate (CGR), dry matter accumulation (DMA), relative growth rate (RGR), ratio of leaf, SPAD, percent relative water content (RWC%), as well as leaf area index (LAI). The nutrient uptake and content was greatly improved by OSA foliar application in fodder maize. The concentration of useful nutrients such as calcium (Ca%), nitrogen (N%) and potassium (K%) significantly increased due to Ortho Silicic Acid (OSA) application; however, the concentration of phosphorus (P%) did not change [49]. Both biofertilisers (seaweed and Ortho Silicic Acid) indicated exceptions which need to be addressed while applying them. The biofertliser Ortho Silicic Acid (OSA) should be supplemented with phosphorous foliar fertilisers to boost phosphorous concentrations to the required level while when using seaweed extract, attention should be paid to the parameters that were not influenced such as stem diameter, plant height and cob number to create more effective fertilisers.

Foliar phosphorus (P) application has been proven to improve maize growth through boosting physiological parameters. The 40.2% net photosynthetic rate, carboxylation, water use efficiency (WUE), and stomatal conductance was attributed to an improved chlorophyll rate (28.8%) and Rubisco activity (24.8%) due to foliar phosphorous fertilisation [62]. The ability of phosphorous to enhance the metabolism of antioxidants, lowering oxidative stress (H_2O_2 and MDA) by 39.1%, makes its timely and precision application important for maize to overcome stress factors such as oxidants [62]. Foliar phosphorous application greatly increased the phosphorous concentration in all parts of the maize plant until the silking stage [30]; therefore, foliar phosphorous supplementation offers an effective strategy toward mitigating phytotoxicity symptoms. The foliar spraying of nano-fertilisers (nano-N or nano-N + nano-Zn) together with 75% basal nitrogen improved maize growth, as well as the biological activity of rhizosphere and yield [63], and it acts as a suitable management approach for nutrient sustainably.

Foliar magnesium application offers an effective alternative mainly when applied at high ratios of K/Mg [64]; however, it is affected by restricted antagonism and an unclear suppression K mechanism affecting the physiological functions of magnesium. Foliar magnesium supplementation improved the rate of net photosynthesis, stomatal conductance, and reduced the concentration of CO_2 within the sub-stomatal and leaf transpiration. The high photosynthetic rate and Rubisco activity led to increased sugar levels in the leaves of maize before grain filling [65]. Additionally, foliar Mg application improved the metabolism of antioxidants, thus protecting the environment against stress [66]. Therefore, the foliar application of magnesium offers a good strategy that increases crop metabolism, which enhances maize growth. Foliar fertilisation using 2% K_2SO_4 proved to be an effective dose enhancing maize growth attributes such as proline (12%), RWC (10%), and total chlorophyll (9%) when maize plants were exposed to severe drought stress conditions [67]. Therefore, the foliar application of K_2SO_4 proved more effective, and it ameliorated drought effects. Foliar molybdenum fertilisation enhances nitrogen metabolism and carbon fixation [68], while the foliar application of zeolite increased the concentration of root nitrogen by 10%, enhancing nitrogen uptake ratios both above and below ground [69].

3.4.2. Grain Yield

Several studies indicate a significant increase in maize yield due to the foliar application of fertilisers. A biofertiliser Ortho Silicic Acid (OSA) applied at a concentration of 0.25% positively influenced both the yield of green fodder (GFY) and dry fodder (DFY) at 53.63 tha^{-1} and DFY 13.35 tha^{-1}, representing increases of 10.6% and 45.3% compared to the control [50]. The maize grain yield increased due to zinc (Zn I, Figure 4) fertilisation from 892 to 2519 $kgha^{-1}$ [60,62]. The foliar application of an effective dose rate of 100 mg Zn l^{-1} yielded 7583.4 $kgha^{-1}$ [61]. The foliar application of both Zn and Fe improved the maize yield, recording values of 5220.5 $kgha^{-1}$ and 4885.5 $kgha^{-1}$ [70]. The manganese foliar application recorded a 19% yield increment when applied at the vegetative stage (V18) at a rate of 0.73 kg $Mnha^{-1}$ [71]. However, Stewart et al. [71] noted that the foliar application of boron, zinc, and iron did not impact grain yield at different rates and time of application. Zinc application showed a 4.5% yield decrease at a split foliar application rate of 0.84 kg Zn ha^{-1} applied at the V11 and V15 stage, which was attributed to the increased concentration of zinc in the leaves beyond the accepted toxicity levels. Foliar phosphorous fertilisation increased grain yield by 21.4% compared to the control [72]. SiAl foliar application at two concentrations (0.5 and 1.0 g L^{-1}) resulted in a greater grain yield [73]. Glutamine (Gln) application at both the silking and dough stages for the maize hybrid ZD958 at a 1.25 mM rate significantly impacted grain yield by 20.0% and 38.0% under different nitrogen levels (sufficient and low, respectively) [74], which is an indication that the effect of glutamine on yield was better under low nitrogen levels compared to sufficient levels. Foliar ZnO application increased grain yield by 17.1% [75].

3.4.3. Grain Quality

The foliar application of fertilisers has proved to be an effective strategy in improving the grain quality of maize. When applied at critical growth stages such as silking and grain filling, foliar fertilisers boost the carbohydrate content, protein content, lipids, kernel size, fibre, mineral content and weight of the maize grain [76]. Rodrigues et al. [51] recorded improved sugar concentration during the grain-filling stage as well as an enhanced antioxidant metabolism, which was a clear indication that foliar fertilisation reduced the effect of environmental stresses. The foliar application of selenium increased grain Se concentration by an average of 18 lg kg^{-1} [77]. Ortho Silicic Acid (OSA) application increased dry matter (11.3%), crude protein (1.3%), and total ash (3.3%) while decreasing neutral detergent fibre (2.0%) and percent acid detergent fibre (2.7%) [49]. Notably, glutamine foliar spray improved the nutritional quality of maize kernels due to an increased concentration of total carotenoids, oil, crude proteins, minerals, unsaturated fatty acids (oleic, and linoleic acids), and α-tocopherol partially resulting from the development of large nutrient-rich embryos [74]. Coupling Urea Ammonium Nitrate (UAN) with waste element S applied through a foliar method in a ratio of 1:1 optimised the maize nutritional status and reduced mineral fertiliser consumption [78]. These findings clearly indicate the impact of foliar fertilisation towards the improvement of grain nutritional quality traits and overall nutritional value of the grain.

Furthermore, research studies have shown that foliar fertilisation enhances the plant's resistance to environmental stressors such as drought, diseases, and nutrient deficiencies, which indirectly contribute to better grain quality. The supply of zinc to maize under zinc-deficient soils was boosted through the application of foliar fertilisers: namely, chitosan and zinc nanoparticles according to [79]. The selenium foliar application in maize achieved higher selenium recovery levels ranging between 52 and 106% [80], and Rajasekar et al. [81] concluded that a foliar application of fertilisers rapidly corrected different plant nutrient deficiencies. While improving nutrient use efficiency and reducing soil nutrient losses, foliar fertilisation ensures the accessibility and availability of nutrients to maize plants essential for optimal growth and development, thus increasing yields and grain quality.

3.5. Fertiliser Application Method (Foliar Application Versus Other Fertiliser Application Methods)

This study indicates the integration of foliar fertilisation with different traditional soil-based fertiliser application methods such as broadcasting and banding to maximise maize growth and yield. Results revealed the application of ZnO-NP through three methods—namely, seed coating, foliar and soil-drench at three levels: 100 mg kg^{-1}, 50 mg kg^{-1} and 150 mg kg^{-1} respectively. All three methods improved the total phosphorous uptake; however, foliar fertilisation improved maize growth by 6–11% and increased biomass by 16–20% [82]. Also, there was an increase in the cob length seed emergence rate, and the plant height increased by 2% compared to the seed coating application method with a positive significant maize growth and yield due to the foliar application of phosphorous doses [83]. The chlorophyll fluorescence parameters positively correlated with different doses of foliar application ($r = 0.8414$); however, fertilisation through soil application showed a positive chlorophyll content ($r = 0.6965$) according to [52]. Khalaf et al. [70] noted that the application of fertilisers through the soil method significantly increased plant mineral uptake (Fe and Zn), while both foliar and fertigation methods significantly improved maize growth and yield. When comparing basal and foliar application methods, Buligon et al. [50] noted no significant effect of both methods on the growth and leaf nutrients of the maize. Foliar phosphorous application was replaced with granular phosphorous, which worked effectively in raising soil phosphorous levels with minimal adverse effects [84]. Also, foliar nitrogen application effectively substituted traditional granular nitrogen application methods for maize grown on permanent beds [85]. An evaluation of the efficiency of foliar application of potassium (K) against other fertilisation methods showed that potassium foliar application increased maize growth, yield, quality and other yield-related components more than fertigation, soil application and splitting. Furthermore, a high net benefit and benefit cost ratio were noted with foliar application [86]. Gazoulis et al. [87] conducted a study which concluded that alternate fertilisation reduced weed biomass (28%) and increased maize yield by 56% compared to conventional fertilisation by enhancing the production of maize. The foliar application of boron increased grain yield by 19.6% compared to both the control and basal application methods [88]. Therefore, foliar fertiliser application offers an efficient alternative to traditional fertiliser application methods. In circumstances where quick nutrient absorption is needed, the direct application of nutrients to plant leaves overcomes soil limitations, such as pH and nutrient lock-up issues, thus ensuring faster nutrient uptake and delivery as well as minimising nutrient losses resulting from leaching and volatilisation. In order to address plant nutrient deficiencies at critical growth stages, foliar application is the effective strategy to promptly boost plant health and productivity. Foliar spraying works effectively alongside other pest or disease control sprays, thus reducing labour costs. However, the studies above have indicated that it works effectively and efficiently as a supplemental approach but does not replace soil fertilisation methods.

4. Research Gaps and Future Directions

4.1. Genotype/Hybrid × Environment × Foliar Fertilisation

Although some studies have documented positive foliar fertilisation effects on maize growth, yield, quality and resilience, there is limited research on the interaction between different maize genotypes, diverse environmental conditions, and foliar nutrient applications. In a study by Wasaya et al. [89], potassium sulphate (K_2SO_4) at a 2% concentration improved growth, water retention, and chlorophyll levels in drought-stressed maize. Zinc fertilisation, particularly through rubber ash, increased grain yield by 62% and decreased cadmium concentration by 57% [90]. Potassium silicate (100 ppm) with ridge planting also increased maize yields under optimal and deficit irrigation [60]. Additionally, silicon and zinc application sustained growth in various water regimes [91], indicating foliar nutrient supplementation as a resilient practice for enhancing maize productivity under challenging conditions. The foliar application of chitosan, selenium and zinc nanoparticles achieved higher selenium recovery levels ranging between 52 and 106% in maize [79,80], and Rajasekar et al. [81] concluded that the foliar application of fertilisers rapidly corrects different plant nutrient deficiencies. Foliar application has proved to significantly boost biomass and phosphorus (P) levels in maize, including root development, allowing plants to utilise P even in deficient conditions [30]. Foliar fertilisation using $ZnSO_4$ and urea enhanced protein, iron (Fe), and manganese (Mn) content in maize grain, particularly when zinc (Zn) was applied together with urea, offering a cost-effective method to increase Zn bioavailability, which is beneficial for human health [91]. However, the long-term use of sulphur-based foliar fertilisers in monoculture maize cultivation depleted essential soil nutrients such as Zn, copper, and Mn, highlighting the need for sustainable soil management [92].

A research gap has shown that there are little or no genetic variation studies in response to foliar treatments across different environmental stressors, such as drought, salinity, and temperature fluctuations. In addition, research on the effect of foliar fertilisation on nutrient efficiency and crop quality amongst different maize hybrids is limited, especially for developing regions with specific climate challenges. Therefore, future studies should be focused on multi-location trials aimed at testing the performance of several maize genotypes under various environmental conditions to understand genotype x environment x foliar fertilisation interactions. Research should emphasise identifying traits in hybrids that maximise foliar fertiliser efficiency and adaptability, particularly under abiotic stress. Genomic studies could help identify genetic markers associated with response to foliar fertiliser treatments, thus guiding breeding programs toward high-yielding, nutrient-efficient hybrids suitable for specific climates under foliar fertilisation.

4.2. Foliar Fertilisation x × Other Agronomic Practices

Limited research studies address the combined effects of foliar fertilisation with agronomic practices such as irrigation, soil fertilisation, planting density, and intercropping. A 2018–2019 field experiment within a maize–wheat cropping system explored how four crop establishment and tillage management (CETM) practices and five phosphorus (P) fertilisation methods affected maize growth and yield. Among CETM approaches, Permanent Raised Bed Zero Tillage (PRBZT) showed the highest growth and yield when combined with a P-fertilisation strategy of 50% basal P, phosphate-solubilising bacteria, arbuscular mycorrhizal fungi, and two foliar sprays [71]. Additionally, intercropping with nitrogen and foliar iron applications significantly improved the chlorophyll, photosynthesis, and yield in maize [93]. Sustainable methods such as inoculating B. subtilis and P. fluorescens with nano-ZnO in tropical regions further enhanced maize's nutritional and biochemical profiles [75]. Several studies evaluate agronomic practices separately, which do not provide proper insights into their combined impact on nutrient uptake, soil health, and crop productivity. Additionally, the impact of foliar fertilisation alongside conservation agriculture practices such as zero-tillage and cover cropping is not well documented, especially regarding sustainable maize production. Future research studies should be focusing on exploring the integrative effects of foliar fertilisation with key agronomic practices, considering both yield optimisation and sustainability. Such research trials, mainly foliar fertilisation coupled with optimised precision irrigation, varied planting densities, and soil fertility management practices could form a backbone for maximising maize yield and growth. Studies on the environmental impact of these combined practices could form a basis for sustainable foliar fertilisation in different farming systems.

5. Conclusions

This study highlighted the potential of the foliar fertilisation technique to enhance nutrient uptake, boost plant physiological growth, and increase crop yields and grain quality as well draw a proper comparison with other fertiliser application methods. The scientific literature revealed that foliar application is the best complementary practice to soil fertilisation and pest management, offering immediate results and helping to optimise the crop growth cycle. Foliar application allowed timely nutrient delivery to maize during critical growth stages, addressing nutrient deficiencies more efficiently than soil-applied fertilisers. Based on the above benefits, maize producers would achieve higher nutrient use efficiency, reduced fertiliser costs and a high profit margin through improved yields, since there is minimised nutrient runoff, reduced environmental pollution and the preservation of soil health. As a result, the resource use is optimised, sustainable agriculture practices are promoted and maize profitability is increased in an environmentally responsible manner. However, the effectiveness of foliar fertilisation depends on factors such as the timing of application, nutrient composition, concentration, and environmental conditions. Further research is recommended to optimise application practices and tailor foliar formulations to specific maize varieties and regional requirements, ensuring sustainable and economically viable production improvements for farmers.

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