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RESEARCH ARTICLE

Impact of planting systems and nutrient management on growth and yield of maize and soybean in a maize + soybean cropping system

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Abstract

A field experiment was conducted during Kharif 2023 at Lovely Professional University, Punjab, using a split-plot design (SPD) with five main plot treatments and five subplot treatments, replicated three times, to evaluate the effects of intercropping and nutrient management on maize growth and productivity. The main plot treatments consisted of cropping systems: Sole maize (M_1), Sole soybean (M_2), Maize + Soybean (1:1, M_3), Maize + Soybean (1:2, M_4) and Maize + Soybean (2:3, M_5). Subplot treatments included nutrient management strategies: Absolute control (S_1), 100% RDF through inorganic fertilizers (S_2), 70% RDF + NPK nano fertilizer spray (S_3), 70% RDF + homemade NPK spray (S_4) and 70% RDF + plant extract NPK spray (S_5). Results indicated that monocropped maize and soybean systems outperformed intercropping in terms of growth and grain yield, with similar trends observed for stover yield. Among nutrient management practices, foliar application of plant extract NPK showed the most significant improvement, enhancing growth attributes and crop growth rate (CGR) by 14.1% in maize and 43.4% in soybean and increasing productivity by 18% in maize and 30.6% in soybean compared to the control. The interaction of maize and soybean with foliar plant extract NPK spray led to grain yield increases of 36.6% in maize and 50.7% in soybean compared to untreated controls. Furthermore, the crop equivalent yield and land equivalent ratio were maximized in the maize-soybean intercropping system at a 1:1 ratio. This study underscores the role of strategic nutrient management and intercropping in optimizing maize and soybean productivity, with foliar NPK plant extract spray showing the most promising results for enhancing growth and yield.

Keywords

Intercropping; Plant extract NPK; Nano fertilizer; Crop equivalent yield; LER

Introduction

Global hunger is becoming an increasingly critical issue, exacerbated by factors such as population growth, urbanization, environmental degradation and climate change (1, 2). To mitigate food shortages, many nations, including India, have adopted intercropping systems. Intercropping, the practice of growing two or more crops on the same plot of land, is a vital agronomic strategy to meet the food demands of a rapidly growing global population (3). It is estimated that approximately 15-20% of the world's food supply is produced through intercropping systems (4). Among various intercropping combinations, cereal-legume intercropping has been recognized as a traditional and effective practice, particularly in tropical agricultural systems (5). This approach enhances spatiotemporal resource utilization by combining crops with differing root systems, such as deep tap-rooted legumes and adventitious-rooted cereals, as well as crops with varying growth heights (6). Leguminous crops, due to their ability to fix atmospheric nitrogen, play a key role in improving soil fertility and contributing to sustainable farming practices (7). Among cereal-legume intercropping combinations, maize (*Zea mays* L.) and soybean (*Glycine max* L.) have been frequently identified as optimal partners due to their complementary growth traits (8). Maize, one of the world's most important cereal crops, is cultivated on approximately 193.7 million hectares globally (9). In India, maize occupies a significant agricultural area, with 9.89 million hectares under cultivation as of 2005, positioning the country as the fourth-largest maize grower (10). Maize serves as a major source of food and feed, as well as a potential bioenergy resource (11). In contrast, soybean, a leguminous crop rich in protein and oil, contributes significantly to both human nutrition and soil fertility through nitrogen fixation (12). These attributes make soybean an important crop for enhancing both agricultural productivity and soil health. During the same planting season, maize, as a nitrogen-consuming C_4 crop and soybean, a nitrogen-fixing C_3 crop, form a symbiotic agricultural duo, ideal for mechanized cultivation and harvesting (13). While nitrogen for soybean is largely supplied by symbiotic bacteria in its roots, optimal nitrogen management becomes crucial when these bacteria are not sufficiently active, ensuring robust early plant development (14). Thus, fertilizer application stands at the heart of contemporary agricultural practices, vital for maximizing crop yields and sustaining food security. Nano NPK fertilizers, in particular, show great promise in mitigating environmental stresses, such as drought, by enhancing plant resilience and boosting soil microbial activity (15). Their flexibility is especially valuable in the era of climate change and dwindling natural resources. Moreover, integrating plant extracts into agronomic methods presents a sustainable and viable alternative to traditional fertilizers. These extracts act as biostimulants, driving growth, improving nutrient absorption and strengthening resistance to pests. Through bioactive compounds, they not only optimize physiological processes but also fortify crops against environmental stressors, boosting yield (16). Additionally, homemade nutrient sources like fermented kitchen waste, horse manure and fruit waste offer a rich supply of beneficial microbes and essential nutrients, further promoting crop health and growth by enhancing soil vitality and microbial diversity (17).

The foliar application of plant extracts, homemade NPK and nano NPK fertilizers plays a crucial role in enhancing agricultural productivity by improving chlorophyll content, promoting growth and increasing the concentration of key metabolites such as rutin, phenylalanine and tryptophan, thereby enriching the nutritional profile of the crops (17). Nano NPK fertilizers, in particular, significantly enhance nutrient use efficiency (NUE) by reducing nutrient losses through leaching and runoff. These fertilizers provide a controlled release of macronutrients, ensuring a continuous supply of essential nutrients during critical stages of crop growth, which is vital for optimizing yield potential (17). In maize-soybean intercropping systems, the complementary resource use patterns of the two crops-due to their distinct root architecture and nutrient requirements-improve overall system efficiency. While maize requires higher nitrogen inputs, soybean contributes to soil fertility through its nitrogen-fixing ability, creating a synergistic relationship between the two. Optimizing row proportions is essential for maximizing the benefits of intercropping and must be adjusted according to local environmental conditions and management practices. Different row arrangements, such as 1:1, 1:2, 2:1, or 2:2 (maize to soybean), influence crop performance by affecting light interception, nutrient uptake and spatial resource utilization. The combined canopy cover in intercropped systems offers enhanced protection against soil erosion from wind and water. However, precise row spacing is critical to ensure that maize's height does not overshadow soybean plants, allowing adequate light penetration for soybean growth. Proper management of row spacing can lead to improved yields for both crops. Despite the potential advantages, current research lacks comprehensive data on the optimal row configurations for maize-soybean intercropping under different nutrient regimes, including both organic inputs (e.g., plant extracts and homemade NPK) and inorganic fertilizers. Moreover, there is a need for more in-depth studies on the impact of various nutrient application methods on crop performance and productivity.

This knowledge gap underscores the significance of the present investigation, which aims to elucidate the most suitable intercropping row proportions in conjunction with appropriate nutrient source combinations. The study seeks to identify strategies that enhance crop growth and maximize productivity for both maize and soybeans in the context of a changing climate scenario. By examining the interplay between spatial arrangements and nutrient management, this research endeavors to provide valuable insights for optimizing intercropping systems, potentially leading to more resilient and productive agricultural practices in the face of evolving environmental challenges.

Materials and Methods

The experiment was conducted at the Agricultural Research Farm of Lovely Professional University, Kapurthala district, Punjab, during the Kharif season of 2023-24. The experimental site, situated at a latitude of 31°22'31.81" N and a longitude of 75°23'03.02" E, is part of the central plain zone of Punjab's agro-climatic regions, specifically within the trans-Gangetic plains of India, with an average elevation of 252 m above mean sea level. The maize and soybean varieties used in this study were 'NK 7328' and 'SL 958,' respectively. Healthy, treated seeds were sown at the appropriate row ratios at the onset of the monsoon during the first week of June. Prior to sowing, soybean seeds were treated with Rhizobium and Pseudomonas cultures at a rate of 500 g ha^{-1} to promote nitrogen fixation and enhance plant growth. The field was marked to ensure accurate row and intra-row spacing for the treatments. The soil type at the experimental site was sandy loam with medium organic carbon content (0.52%), low available nitrogen (216 kg ha^{-1}), medium phosphorus (P_2O_5 at 34 kg ha^{-1}) and available potassium (K_2O at 210 kg ha^{-1}). Fertilizers were applied as per the recommended dose using urea, diammonium phosphate (DAP) and muriate of potash (MOP). Additional fertilizer doses were adjusted according to treatment specifications. The experiment followed a split-plot design (SPD) with five main plot factors and five subplot factors, replicated three times. This resulted in a total of 25 treatment combinations for maize-soybean intercropping systems (Table 1).

Statistical analysis

Data analysis and interpretation were conducted using Fisher's analysis of variance (ANOVA), as described by Gomez and Gomez (18). The least significant difference (LSD) test at a significance level of $\alpha \leq 0.05$ and a statistic of 10 were employed to compare the means of the treatment groups.

Results and Discussion

Growth parameters of maize:

***Intercropping effect*:** The mean values of the growth parameters revealed that different planting patterns had significant effects on maize. At harvest, the greatest plant height was recorded at M1 (164.9 cm), followed by M3 (164 cm), which was on par with M4 (163.3 cm). The lowest plant height was recorded for M5 (162 cm). When sole cropping was carried out instead of intercropping with soybeans, the height of maize increased due to less competition for light, water and nutrients, which led to a more ideal growing environment and reduced competition for resources. The leaf area of maize had a positive correlation with plant height; taller plants had a significantly greater leaf area in M1 (6650.2 cm^2 plant^{-1}), followed by M3 (6611.8 cm^2 plant^{-1}), which was also on par with M4 (6584.3 cm^2 plant^{-1}) and the lowest leaf area was observed in M5 (6491.1 cm^2 plant^{-1}), which was 2.4% lower than the superior leaf area. The development of growth attributes such as plant height and leaf area have a positive impact on the CGR. The highest CGR was recorded in M1 (23.7 g m^{-2} day^{-1}), which was on par with that in M3 (23.7 g m^{-2} day^{-1}), and the lowest was recorded in M4 (15.2 g m^{-2} day^{-1}). These results are consistent with those of Yang (13) and Usman (19).

***Nutrient management effect*:** The highest plant height was observed in treatment S_5 (166.5 cm), which was statistically comparable to S_4 (166 cm) and S_3 (165.7 cm), followed by S_2 (165.3 cm). The lowest plant height was recorded in the control, S_1 (154.2 cm). A similar trend was observed in leaf area, where S_5 exhibited the largest leaf area (4635.6 dm^2), representing a 6% increase over the control (S_1). All nutrient management treatments led to comparable crop growth rates, with a rate of 19.5 g m^{-2} day^{-1} for the control. In addition to the primary macronutrients (nitrogen, phosphorus and potassium), plant extract-based NPK sprays often contain beneficial secondary metabolites, plant growth hormones and bioactive compounds that enhance nutrient uptake, promote root growth, and improve overall plant vigor. These organic compounds likely optimize the utilization of applied inorganic fertilizers, contributing to improved plant health and development. Furthermore, plant extracts may stimulate soil microbial activity, enhancing nutrient availability and uptake by maize plants (20). The superior growth performance in S_5 is likely due to the synergistic effect of bioactive components in the plant extract combined with the inorganic fertilizers (21).

***Interaction effect*:** The interaction between intercropping and nutrient management significantly influenced maize plant height. Across all nutrient treatments, except the control, maize mono-cropping resulted in the highest plant height, ranging from 166.7 cm to 167.7 cm. This suggests that maize, when grown alone, benefits from reduced interspecific competition, allowing for optimal access to nutrients. However, even in maize-soybean intercropping systems, particularly at a 1:1 ratio, maize maintained comparable plant height (166 cm to 166.6 cm) under enhanced nutrient management strategies, including 100% RDF, nano NPK spray, homemade NPK spray and plant extract NPK with 70% RDF. These nutrient management practices likely provided sufficient growth-promoting elements and nutrients to support robust maize growth, despite the competition from soybean. In contrast, in a maize-soybean (2:3) intercropping system, where the proportion of soybean was higher, increased competition for resources such as light, water and nutrients likely limited maize growth. The restricted availability of essential nutrients in this competitive environment, along with the absence of supplemental fertilization in the control treatment, resulted in the lowest recorded plant height (149.3 cm). Similar trends were observed in leaf area and crop growth rate (CGR), as these growth parameters are closely tied to the availability of key resources like nutrients, water and light. Adequate nutrient management in less competitive intercropping patterns allowed maize to achieve greater growth metrics, while heightened competition and lack of additional nutrients in control treatments led to reduced growth performance (Table 1).

Grain yield and straw yield of maize

***Intercropping effect*:** The data revealed that the highest test weight was recorded in the maize mono-cropping system, with 119.59 g per 1000 seeds, which was significantly greater than that of the intercropping systems. The lowest test weight was observed in the maize + soybean (2:3) intercropping system, at 115.54 g per 1000 seeds, consistent with findings reported by Mandal et al. (2014). Maize mono-cropping also resulted in the highest grain yield, at 54.6 q ha^{-1}, which was superior to all intercropping configurations. In contrast, the lowest grain yield was recorded for maize + soybean (2:3) intercropping. This outcome can be attributed to interspecies competition in intercropping systems, which tends to reduce maize yield compared to mono-cropping, as supported by prior studies (24). The maize yield was significantly influenced by the maize-legume intercropping system. The highest stover yield was recorded in the maize mono-cropping system, at 76.3 q ha^{-1}, followed by maize + soybean intercropping systems with 1:1 and 1:2 row configurations. The lowest stover yield was observed in the maize + soybean (2:3) intercropping system. These findings align with those reported by Rajeshkumar (25), highlighting the potential trade-offs in yield components when intercropping maize with legumes due to resource competition.

***Nutrient management effect*:** Nutrient management practices significantly influenced test weight, grain yield, and stover yield in maize. The plant extract NPK treatment consistently outperformed the control, demonstrating the highest test weight (120.61 g/1000 seed) and grain yield (53.9 q ha^{-1}). Comparable results were observed with 70% RDF combined with either nano fertilizer spray or homemade NPK spray (118.97 g/1000 seed and 52.7 q ha^{-1}; 117.66 g/1000 seed and 53.1 q ha^{-1}, respectively). These findings suggest that the bioactive substances in plant extracts and the enhanced nutrient absorption capabilities of nano fertilizers contribute to improved plant vigor, stress resistance and ultimately, higher yields. Similar trends were observed for stover yield, with plant extract NPK and 70% RDF + nano fertilizer spray treatments exhibiting significantly higher yields (24.6-26.8%) compared to the control. These results align with previous research on wheat (29), maize (30) and rice (31).

***Interaction effect*:** Sole maize planting combined with foliar application of NPK plant extract yielded the highest grain yield (58.9 q ha^{-1}) and straw yield (81.2 q ha^{-1}). Conversely, the control treatment with maize + soybean intercropping (2:3) resulted in the lowest grain yield (40.6 q ha^{-1}) and stover yield (58 q ha^{-1}). In sole cropping, the absence of interspecies competition and the beneficial effects of plant extract foliar application, including enhanced nutrient uptake and improved plant health due to bioactive compounds, contributed to the superior performance. These positive effects were comparable to those observed with homemade NPK spray and nano NPK spray (Table 1).

Soybean Growth Parameters

***Intercropping effect*:** The mean growth parameters indicate that different planting patterns had significant effects on soybean growth (Table 2, Fig 2). At harvest, the tallest plants were observed in the M2 planting pattern (115.63 cm), followed by M3 (112.64 cm), which was statistically similar to M4 (112.02 cm). The shortest plants were recorded in M5 (110.65 cm). In sole cropping systems, where soybeans were not intercropped with maize, plant height increased due to reduced competition for light, water and nutrients, providing an optimal environment for growth. Leaf area followed a positive correlation with plant height, with M2 producing the largest leaf area (1024.32 cm^2 per plant), followed by M3 (952.70 cm^2 per plant), which was statistically similar to M4 (899.74 cm^2 per plant). The smallest leaf area was recorded in M5 (863.17 cm^2 per plant), representing a 2.4% reduction compared to the highest value. Growth attributes such as increased plant height and leaf area positively influenced the crop growth rate (CGR). The highest CGR, measured 90 days after sowing, was recorded in M2 (8.68 g m^{-2} day^{-1}), which was statistically similar to M3 (8.54 g m^{-2} day^{-1}), while the lowest CGR was observed in M4 (8.03 g m^{-2} day^{-1}). These findings align with previous studies by Usman and Yang (13-19), demonstrating that optimized planting patterns enhance soybean growth performance.

***Nutrient management effect*:** The highest plant height was observed in treatment S_5, measuring 115.14 cm, which was statistically comparable to S_4 (114.7 cm) and S_3 (114.42 cm). This was followed by S_2 at 114 cm, while the control group S_1 recorded the lowest height at 102.92 cm. A similar trend was noted for leaf area, with S_5 achieving the largest leaf area of 966.83 dm^2, representing a 13.8% increase compared to S_1 (control). Under varying nutrient management practices, all nutrient combinations produced comparable crop growth rates to the control, which had a growth rate of 6.42 g m^{-2} day^{-1}. In addition to the primary macronutrients (nitrogen, phosphorus and potassium), NPK sprays derived from plant extracts often contain a diverse array of beneficial secondary metabolites, plant growth regulators and bioactive compounds that enhance nutrient uptake, promote root development and improve overall plant vigor. These organic substances can significantly improve plant health and growth by optimizing the utilization of applied inorganic fertilizers. Furthermore, plant extracts may stimulate soil microbial activity, thereby enhancing nutrient availability and uptake in maize plants (20). The superior growth performance observed in S5 is likely attributed to the synergistic interactions between the bioactive components of the plant extract and the inorganic fertilizers (21).

***Interaction effect*:** The interaction between intercropping and nutrient management significantly influenced the plant height of soybean plants. All nutrient combinations, with the exception of the control, positively affected plant height in monocropped soybean, increasing it from 115.35 cm to 116.37 cm. When interplanted with maize at a 1:1 ratio and supplemented with enhanced nutrient management strategies-such as 100% recommended dose of fertilizers (RDF), nano NPK sprays, homemade NPK sprays, and plant extract NPK with 70% RDF-soybeans benefited from sufficient nutrient availability to support optimal growth. These nutrient management practices likely provide essential growth-promoting elements that enable maize to achieve notable heights, ranging from 166 cm to 166.6 cm. Conversely, the higher proportion of soybean in the maize-soybean (2:3) intercropping system appears to increase competition for resources. This heightened competition, combined with the control treatment that lacked additional nutrient supplementation, severely restricts the availability of essential nutrients and growth factors, resulting in the lowest recorded plant height of 98.0 cm. Similar trends were observed in leaf area and crop growth rate (CGR), as these parameters are also directly affected by the availability of light, water and nutrients (22-23). Effective nutrient management in less competitive planting arrangements enables maize to attain superior growth metrics, while increased competition and insufficient nutrient supply in control treatments lead to diminished growth performance (Table 2).

Table 1. Detailed information's of treatment combinations.

Sl. no.	Treatment	Details
M1S1	Sole maize with control	Maize alone sown with spacing of 60 cm row to row and 20 cm plant to plant and there is no fertilizer application here
M1S2	sole maize with 100% RDF	The sole maize was sown with 100% recommended dose of fertilizer which are supplied through urea, DAP and MOP. And 60 × 20 cm spacing between row to row and plant to plant were maintained.
M1S3	Sole maize with 70%RDF and Nano NPK	Maize was sown as a sole crop with a spacing of 60 × 20 cm, and 70% of the recommended dose of fertilizer (RDF) was applied at sowing. Additionally, foliar applications of nano NPK were made twice during the growing season, at 35 and 65 days after sowing (DAS).
M1S4	Sole maize with 70% RDF and Homemade NPK	Maize was sown as a sole crop with a spacing of 60 × 20 cm. At the time of sowing, 70% of the recommended dose of fertilizer (RDF) was applied. Additionally, a homemade NPK solution was sprayed twice, at 35 and 65 days after sowing (DAS). This homemade fertilizer was prepared by fermenting a mixture of kitchen waste, jaggery, and horse dung in an airtight drum. After fermentation, the solution was filtered and its nutrient content was quantified before application.
M1S5	Sole maize with 70%RDF + plant extract	Maize was sown as a sole crop with a spacing of 60 × 20 cm. At the time of sowing, 70% of the recommended dose of fertilizer (RDF) was applied. Additionally, a plant extract solution was sprayed twice, at 35 and 65 days after sowing (DAS).
M2S1	Sole Soybean with control	Soybean alone sown with spacing of 30 cm row to row and 5 cm plant to plant and there is no fertilizer application here
M2S2	sole maize with 100% RDF	The sole Soybean was sown with 100% recommended dose of fertilizer which are supplied through urea, DAP and MOP. And 30 × 5 cm spacing between row to row and plant to plant were maintained.
M2S3	Sole Soybean with 70%RDF and Nano NPK	Soybean was sown as a sole crop with a spacing of 30 × 5 cm, and 70% of the recommended dose of fertilizer (RDF) was applied at sowing. Additionally, foliar applications of nano NPK were made twice during the growing season, at 35 and 65 days after sowing (DAS).
M2S4	Sole Soybean with 70% RDF and Homemade NPK	Soybean was sown as a sole crop with a spacing of 30 × 5 cm. At the time of sowing, 70% of the recommended dose of fertilizer (RDF) was applied. Additionally, a homemade NPK solution was sprayed twice, at 35 and 65 days after sowing (DAS). This homemade fertilizer was prepared by fermenting a mixture of kitchen waste, jaggery, and horse dung in an airtight drum. After fermentation, the solution was filtered and its nutrient content was quantified before application.
M2S5	Sole Soybean with 70%RDF+ plant extract	Soybean was sown as a sole crop with a spacing of 30 × 5 cm. At the time of sowing, 70% of the recommended dose of fertilizer (RDF) was applied. Additionally, a plant extract solution was sprayed twice, at 35 and 65 days after sowing (DAS).
M3S1	Maize + Soybean (1:1) with control	Maize was sown with a spacing of 60 × 20 cm, with one row of soybean intercropped between every two rows of maize. No fertilizer was applied to this intercropping system.
M3S2	Maize + Soybean (1:1) with 100% RDF	Maize was sown with a spacing of 60 × 20 cm, with one row of soybean intercropped between every two rows of maize. The 100% RDF was applied to this intercropping system.
M3S3	Maize + Soybean (1:1) with 70%RDF and Nano NPK	Maize was sown with a spacing of 60 × 20 cm, with one row of soybean intercropped between every two rows of maize. The 70% RDF was applied to this intercropping system. Additionally, foliar applications of nano NPK were made twice during the growing season, at 35 and 65 days after sowing (DAS).
M3S4	Maize + Soybean (1:1) with 70% RDF and Homemade NPK	Maize was sown with a spacing of 60 × 20 cm, with one row of soybean intercropped between every two rows of maize. The 70% RDF was applied to this intercropping system. Additionally, foliar applications of homemade NPK were applied twice during the growing season, at 35 and 65 days after sowing (DAS).
M3S5	Maize + Soybean (1:1) with 70%RDF+ plant extract	Maize was sown with a spacing of 60 × 20 cm, with one row of soybean intercropped between every two rows of maize. The 70% RDF was applied to this intercropping system. Additionally, foliar applications of plant extract were applied twice during the growing season, at 35 and 65 days after sowing (DAS).
M4S1	Maize + Soybean (1:2) with control	Maize was sown with a spacing of 90 × 20 cm with two rows of soybean intercropped between every two rows of maize. No fertilizer was applied to this intercropping system.
M4S2	Maize + Soybean (1:2) with 100% RDF	Maize was sown with a spacing of 90 × 20 cm with two rows of soybean intercropped between every two rows of maize. The 100% RDF was applied to this intercropping system.
M4S3	Maize + Soybean (1:2) with 70%RDF and Nano NPK	Maize was sown with a spacing of 90 × 20 cm with two rows of soybean intercropped between every two rows of maize. The 70% RDF was applied to this intercropping system. Additionally, foliar applications of nano NPK were made twice during the growing season, at 35 and 65 days after sowing (DAS).
M4S4	Maize + Soybean (1:2) with 70% RDF and Homemade NPK	Maize was sown with a spacing of 90 × 20 cm with two rows of soybean intercropped between every two rows of maize. The 70% RDF was applied to this intercropping system. Additionally, foliar applications of homemade NPK were applied twice during the growing season, at 35 and 65 days after sowing (DAS).
M4S5	Maize + Soybean (1:2) with 70%RDF+ plant extract	Maize was sown with a spacing of 90 × 20 cm with two rows of soybean intercropped between every two rows of maize. The 70% RDF was applied to this intercropping system. Additionally, foliar applications of plant extract were applied twice during the growing season, at 35 and 65 days after sowing (DAS).
M5S1	Maize + Soybean (2:3) with control	In this intercropping system, maize was sown with a spacing of 60 × 20 cm, while soybean was sown at 30 × 5 cm intervals. The arrangement consisted of two rows of maize followed by three rows of soybean, alternating throughout the field. No fertilizer was applied to this intercropped cultivation.
M5S2	Maize + Soybean (2:3) with 100% RDF	In this intercropping system, maize was sown with a spacing of 60 × 20 cm, while soybean was sown at 30 × 5 cm intervals. The arrangement consisted of two rows of maize followed by three rows of soybean, alternating throughout the field. The 100% fertilizer was applied to this intercropped cultivation.
M5S3	Maize + Soybean (2:3) with 70%RDF and Nano NPK	In this intercropping system, maize was sown with a spacing of 60 × 20 cm, while soybean was sown at 30 × 5 cm intervals. The arrangement consisted of two rows of maize followed by three rows of soybean, alternating throughout the field. The 70% fertilizer was applied to this intercropped cultivation. Additionally, foliar applications of nano NPK were made twice during the growing season, at 35 and 65 days after sowing (DAS).
M5S4	Maize + Soybean (2:3) with 70% RDF and Homemade NPK	In this intercropping system, maize was sown with a spacing of 60 × 20 cm, while soybean was sown at 30 × 5 cm intervals. The arrangement consisted of two rows of maize followed by three rows of soybean, alternating throughout the field. The 70% fertilizer was applied to this intercropped cultivation. Additionally, foliar applications of homemade NPK were made twice during the growing season, at 35 and 65 days after sowing (DAS).
M5S5	Maize + Soybean (2:3) with 70%RDF+ plant extract	In this intercropping system, maize was sown with a spacing of 60 × 20 cm, while soybean was sown at 30 × 5 cm intervals. The arrangement consisted of two rows of maize followed by three rows of soybean, alternating throughout the field. The 70% fertilizer was applied to this intercropped cultivation. Additionally, foliar applications of plant extract were made twice during the growing season, at 35 and 65 days after sowing (DAS).

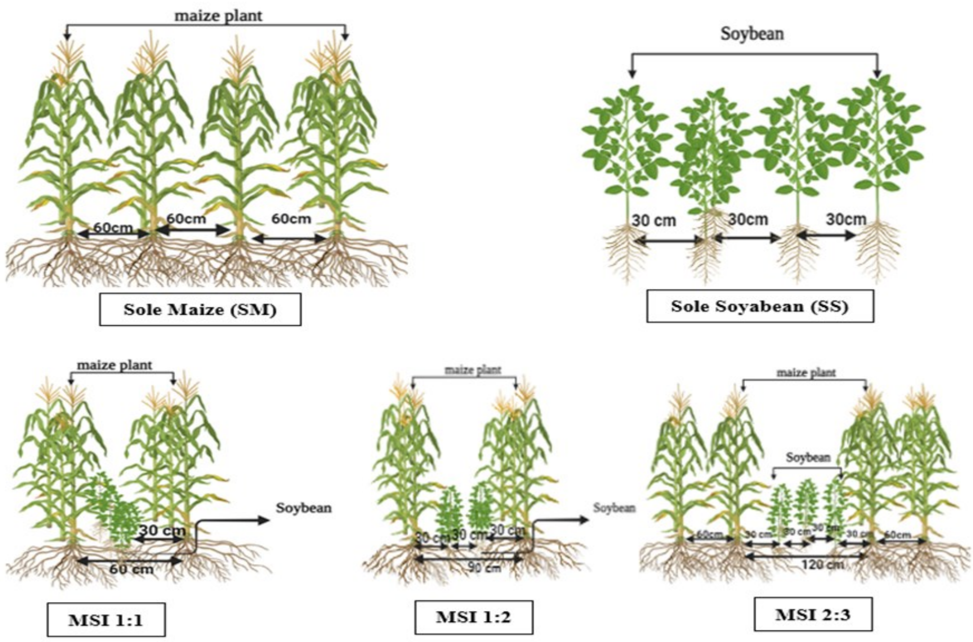

Fig 1. Planting geometry under the maize soybean intercropping system

Table 2. Effect of intercropping and nutrient management on growth and productivity of maize

Treatment	Plant height (cm)	Leaf Area (cm^{2} plant^{-1})	CGR (g m^{2} day^{-1})	Test weight (g)	Grain yield (q ha^{-1})	Stover yield (q ha^{-1})	MEY (q ha^{-1})
Cropping system							
M$_1$	164.99^{a}	6650.28^{a}	23.79^{a}	119.59^{a}	55.77^{a}	76.44^{a}	55.77^{d}
M$_2$	-	-	-	-	-	-	-
M$_3$	164.00^{b}	6611.89^{ab}	23.71^{a}	118.26^{ab}	52.7^{b}	74.09^{b}	100.48^{a}
M$_4$	163.38^{b}	6584.30^{b}	15.26^{c}	117.11^{b}	49.32^{c}	69.42^{c}	93.08^{b}
M$_5$	162.01^{c}	6491.11^{c}	22.08^{b}	115.54^{b}	45.88^{d}	65.12^{d}	85.72^{c}
SEM (±)	0.22	14.76	0.18	0.64	0.39	0.63	1.54
C.D(0.05)	0.79	52.07	0.64	2.27	1.37	2.23	5.44
Nutrient source							
S$_1$	154.28^{c}	6395.12^{c}	19.15^{b}	114.06^{d}	42.19^{c}	59.25^{c}	69.54^{d}
S$_2$	165.36^{b}	6591.53^{b}	21.62^{a}	116.83^{c}	52.31^{b}	73.37^{b}	85.46^{c}
S$_3$	165.78^{ab}	6631.43^{ab}	21.67^{a}	117.66^{b}	53.08^{ab}	74.13^{ab}	87.10^{bc}
S$_4$	166.06^{ab}	6632.03^{ab}	21.75^{a}	118.97^{ab}	53.12^{ab}	74.45^{ab}	87.46^{ab}
S$_5$	166.50^{a}	6671.87^{a}	21.88^{a}	120.61^{a}	53.89^{a}	75.13^{a}	89.26^{a}
SEM (±)	0.31	14.16	0.11	0.64	0.28	0.49	1.90
C.D(0.05)	0.89	40.98	0.32	2.27	1.83	1.42	0.65
Interaction (A×B)							
M1S1	156.62^{f}	6400.3^{e}	20.93^{c}	116.0	48.35^{f}	60.77^{f}	48.35^{l}
M1S2	166.71^{abcd}	6698.9^{a}	24.33^{a}	118.767	56.57^{bc}	79.38^{abc}	56.57^{k}
M1S3	166.85^{abc}	6715.5^{a}	24.43^{a}	119.767	57.45^{abc}	80.24^{ab}	56.99^{k}
M1S4	167.03^{ab}	6716.3^{a}	24.56^{a}	120.700	57.5^{ab}	80.51^{ab}	57.5^{k}
M1S5	167.73^{a}	6720.3^{a}	24.69^{a}	122.733	59^{a}	81.28^{a}	59^{k}
M2S1	-	-	-	-	-	-	-
M2S2	-	-	-	-	-	-	-
M2S3	-	-	-	-	-	-	-
M2S4	-	-	-	-	-	-	-
M2S5	-	-	-	-	-	-	-
M3S1	156.03^{f}	6399.6^{e}	21.06^{c}	114.500	41.95^{g}	59.78^{f}	79.19^{j}
M3S2	164.90^{e}	6647.5^{ab}	24.27^{a}	117.433	54.4^{d}	76.28^{d}	103.5^{bcd}
M3S3	166.00^{abcd}	6659.9^{ab}	24.30^{a}	118.300	55.48^{cd}	77.54^{d}	105.2^{abc}
M3S4	166.42^{abcde}	6660.5^{ab}	24.39^{a}	120.250	55.5^{bcd}	78.08^{d}	105.6^{ab}
M3S5	166.63^{abcde}	6692.0^{a}	24.51^{a}	120.800	56.12^{bc}	78.74^{d}	108.73^{a}
M4S1	155.10^{f}	6388.8^{e}	13.98^{e}	113.300	40.24^{g}	58.42^{f}	77.43^{j}
M4S2	164.96^{de}	6530.3^{cd}	15.53^{d}	116.433	51.17^{e}	71.67^{e}	94.65^{fgh}
M4S3	165.22^{cde}	6660.3^{ab}	15.54^{d}	117.200	51.5^{e}	71.99^{e}	96.48^{efg}
M4S4	165.61^{bcde}	6661.1^{ab}	15.56^{d}	118.133	51.51^{e}	72.11^{e}	97.67^{def}
M4S5	166.10^{abcde}	6681.0^{ab}	15.68^{d}	120.467	52.18^{e}	72.91^{e}	99.12^{cde}
M5S1	149.36^{g}	6391.7^{e}	20.60^{c}	112.433	38.21^{h}	58.04^{f}	73.18^{j}
M5S2	164.89^{e}	6489.4^{d}	22.31^{b}	114.667	47.11^{f}	66.13^{f}	87.11^{i}
M5S3	165.05^{de}	6490.0^{d}	22.39^{b}	115.367	47.91^{f}	66.75^{f}	88.46^{hi}
M5S4	165.17^{cde}	6490.2^{d}	22.46^{b}	116.800	47.91^{f}	67.08^{f}	89.03^{hi}
M5S5	165.52^{bcde}	6594.2^{bc}	22.64^{b}	118.433	48.25^{f}	67.58^{f}	90.47^{ghi}

***Figures not sharing the same letters in the same column differ significantly at $p<0.05$

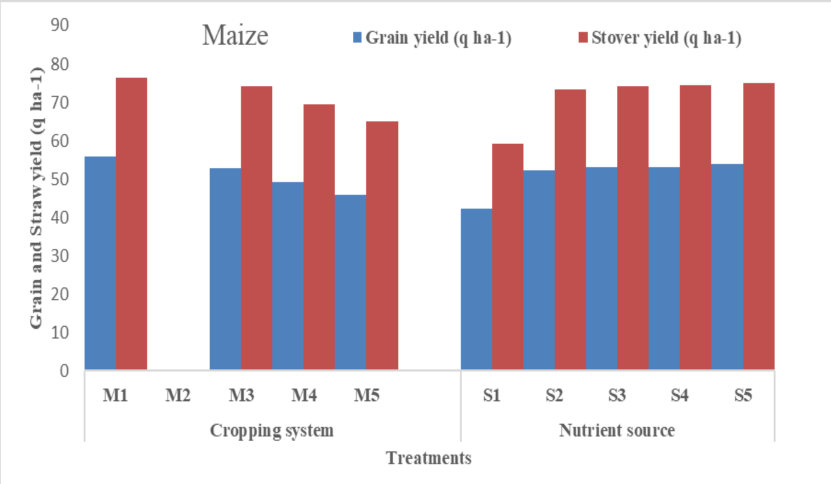

Fig. 2. Graphical representation of grain and straw yield of maize

Test weight, grain and straw yield of Soybean

***Intercropping effect*:** The highest test weight per 1000 seeds was observed in the sole soybean cropping system, recording 118.04 g, which was significantly greater than that of the other intercropping systems. Conversely, the lowest test weight was noted in the maize + soybean (2:3) intercropping system, at 110.97 g per 1000 seeds (Table 3 and Fig 3). The monocropped soybean system achieved the highest grain yield at 22.36 q ha^{-1}, outperforming all intercropping systems, while the maize + soybean (2:3) intercropping system yielded the least. These findings suggest that monocropping soybean results in greater yields compared to intercropped soybean, likely due to interspecific competition within the intercropping systems (32-33). In terms of stover yield, the maize + legume intercropping system influenced soybean production. The maximum stover yield for maize was recorded in the sole soybean system at 30.37 q ha^{-1}, followed by the maize + soybean intercropping systems at ratios of 1:1 and 1:2. The lowest stover yield occurred in the maize + soybean (2:3) intercropping system. These results align with the findings reported by Young (34).

***Nutrient management effect*:** The test weight (g) and grain and stover yields of maize exhibited significant differences across various nutrient management practices (Table 3 and Fig 3). The highest test weight was recorded with the plant extract NPK treatment, yielding 115.82 g per 1000 seeds and corresponding to a grain yield of 22.06 q ha^{-1}. This was comparable to the 70% recommended dose of fertilizers (RDF) combined with NPK fertilizer spray, which yielded a test weight of 115.31 g (52.7 q ha^{-1}) and the 70% RDF combined with homemade NPK spray, yielding 115.03 g (21.53 q ha^{-1}). The superior test weight and grain yield observed in these treatments can be attributed to the presence of bioactive compounds that enhance overall plant vigor and stress resilience by promoting root development and nutrient uptake (26). Additionally, nano fertilizers positively influence plant physiology by significantly increasing root biomass, thereby enhancing nutrient absorption from the soil rhizosphere, which ultimately contributes to improved yield attributes (27-28). A similar trend was observed in stover yield, with the plant extract NPK treatment yielding 16.9% to 19.4% more stover compared to the control and this yield was comparable to that of plants receiving 70% RDF with homemade NPK. These findings align with the research conducted by Raza in 2019 (23).

***Interaction effect*:** The interaction effect of sole soybean planting combined with foliar application of NPK plant extract resulted in the highest test weight (115.82 g/1000 seeds), grain yield (22.06 q ha^{-1}) and straw yield (29.49 q ha^{-1}). In contrast, the control treatment, which involved maize-soybean intercropping at a 2:3 ratio, showed significantly lower values for test weight (113.91 g), grain yield (16.88 q ha^{-1}) and straw yield (24.68 q ha^{-1}). In the sole cropping system, competition among plants was minimal, allowing the foliar application of plant extracts to effectively enhance nutrient uptake and improve overall plant health through the action of bioactive compounds. These plant extracts may positively influence soil nutrient dynamics, particularly enhancing phosphorus absorption under certain conditions (39). Additionally, they facilitate nutrient absorption and enhance plant health by inducing physiological responses, such as increased root hair length and density, as well as modulating enzyme activity involved in metabolic processes (37). Notably, the results were comparable to those obtained with foliar applications of homemade NPK and nano NPK sprays (Table 2).

Crop equivalent yield (CEY) and LER of intercropping

The data indicate that the highest maize equivalent yield (MEY) was achieved in the maize-soybean (1:1) intercropping system, recording a yield of 100.48 q ha^{-1}, which surpassed the yields observed in other intercropping configurations. In contrast, the lowest grain yield was noted in the sole cropping system, at 55.77 q ha^{-1}. This trend suggests that the maize-soybean (1:1) intercropping arrangement is superior to other intercropping combinations due to the synergistic effects of this particular pairing (34). Soil equivalent yield (SEY) and land equivalent ratio (LER) demonstrated similar trends, further supporting the enhanced yield outcomes associated with this intercropping system. The increase in yield parameters can be attributed primarily to the efficient utilization of resources, including space, nutrients and light, compared to other intercropping systems. These findings align with those of Avil-Kumar (35), who highlighted the intercropping advantage reflected in positive monetary gains.

Table 3. Effect of intercropping and nutrient management on growth and productivity of soybean and land equivalent ratio.

Treatment	Plant height (cm)	Leaf area (cm^{2})	CGR (gm^{-2}d^{-1})	Grain yield (q ha^{-1})	Test weight (g)	Stover yield (q ha^{-1})	SEY (q ha^{-1})	LER
				Cropping system				
M1	-	-	-	-	-	-	-	1^{d}
M2	113.63^{a}	1024.32^{a}	8.68^{a}	22.36a	118.04^{a}	30.37^{a}	22.36^{d}	1^{d}
M3	112.64^{b}	952.70^{b}	8.54^{a}	21.71b	116.44^{b}	28.78^{b}	45.69^{a}	1.90^{a}
M4	112.02^{b}	899.74^{c}	8.03^{b}	19.79c	114.26^{c}	26.99^{c}	42.33^{b}	1.76^{b}
M5	110.65^{c}	863.17^{d}	8.08^{b}	18.22d	110.97^{d}	25.63^{d}	39.26^{c}	1.62^{c}
SEM (±)	0.24	2.6	0.12	0.22	0.07	0.38	0.29	0.01
C.D(0.05)	0.85	9.31	0.42	0.76	0.27	1.33	1.03	0.03
				Nutrient source				
S1	102.92^{c}	832.66^{c}	6.42^{a}	16.88c	113.91^{d}	24.68c	31.06^{c}	1.44^{a}
S2	114.00^{b}	944.60^{b}	8.44^{ab}	20.9b	114.57^{c}	27.99b	38.24^{b}	1.45^{a}
S3	114.42^{ab}	965.12^{ab}	8.78^{ab}	21.24ab	115.03^{b}	28.68ab	38.74^{b}	1.46^{a}
S4	114.7^{ab}	965.70^{ab}	8.8^{b}	21.53ab	115.31^{ab}	28.87ab	39.14^{ab}	1.46^{a}
S5	115.14^{a}	966.83^{a}	9.21^{c}	22.06a	115.82^{a}	29.49a	39.88^{a}	1.46^{a}
SEM (±)	0.36	7.66	0.23	0.25	0.12	0.88	0.30	0.003
C.D(0.05)	0.88	22.17	0.67	0.74	0.36	0.30	0.86	NA
				Interaction (M*N)				
M1S1	-	-	-	-	-	-	-	1^{e}
M1S2	-	-	-	-	-	-	-	1^{e}
M1S3	-	-	-	-	-	-	-	1^{e}
M1S4	-	-	-	-	-	-	-	1^{e}
M1S5	-	-	-	-	-	-	-	1^{e}
M2S1	105.26^{f}	838.9^{f}	7.94^{b}	17.99^{ij}	114.89 ^{e}	25.93^{def}	17.992^{i}	1^{e}
M2S2	115.35^{abcd}	1059.3^{a}	8.38^{ab}	23.35^{ab}	118.14 ^{b}	31.66^{a}	23.35^{h}	1^{e}
M2S3	115.49^{abc}	1074^{a}	8.82^{ab}	23.60^{ab}	118.91 ^{a}	31.77^{a}	23.60^{h}	1^{e}
M2S4	115.67^{ab}	1074.2^{a}	8.91^{ab}	23.71^{ab}	119.21 ^{a}	31.78^{a}	23.71^{h}	1^{e}
M2S5	116.37^{a}	1075.2^{a}	9.30^{a}	23.96^{a}	119.57 ^{a}	32.24^{a}	23.96^{h}	1^{e}
M3S1	104.67^{f}	835.1^{f}	6.41^{c}	16.92^{jk}	114.62 ^{e}	24.65^{ef}	35.98^{f}	1.80^{b}
M3S2	113.54^{e}	970.6^{b}	9.137^{ab}	22.31^{bcd}	116.71 ^{d}	30.26^{ab}	47.02^{b}	1.91^{a}
M3S3	114.64^{abcde}	985.4^{b}	8.753^{ab}	22.71^{abc}	116.91 ^{cd}	30.47^{a}	47.81^{ab}	1.93^{a}
M3S4	115.06^{abcde}	985.9^{b}	8.88^{ab}	22.76^{abc}	117.21 ^{cd}	30.48^{a}	48.00^{ab}	1.92^{a}
M3S5	115.27^{abcde}	986.5^{b}	9.52^{a}	23.84^{a}	117.57 ^{bc}	31.27^{a}	49.40^{a}	1.94^{a}
M4S1	103.74^{f}	831.2^{f}	5.73^{c}	16.89^{jk}	113.76 ^{f}	24.54^{f}	35.17^{f}	1.76^{b}
M4S2	113.53^{e}	904.9^{cd}	7.97^{b}	19.75^{fgh}	114.18 ^{ef}	27.60^{cd}	43.00^{d}	1.74^{bc}
M4S3	113.86^{cde}	919.9^{cd}	8.75^{ab}	20.51^{efg}	114.63 ^{e}	28.14^{c}	43.83^{cd}	1.76^{b}
M4S4	114.25^{bcde}	920.6^{cd}	8.62^{ab}	20.97^{def}	114.67 ^{e}	28.17^{c}	44.37^{cd}	1.78^{b}
M4S5	114.74^{abcde}	922.1^{c}	9.04^{ab}	21.26^{cde}	114.90 ^{e}	28.27^{bc}	45.03^{c}	1.77^{b}
M5S1	98.00^{g}	825.5f	5.58^{c}	15.89^{k}	112.36 ^{g}	24.22^{f}	33.25^{g}	1.67^{cd}
M5S2	113.6^{de}	843.6ef	8.27^{ab}	18.17^{ij}	110.31 ^{i}	25.07^{ef}	39.57^{e}	1.60^{d}
M5S3	113.69^{de}	881.2de	8.79^{ab}	18.59^{hi}	110.60 ^{hi}	26.60^{cde}	40.19^{e}	1.62^{d}
M5S4	113.81^{cde}	882.1cde	8.77^{ab}	18.68^{hi}	111.01 ^{hi}	26.64^{cde}	40.45^{e}	1.62^{d}
M5S5	114.16^{bcde}	883.5cde	8.97^{ab}	19.18^{ghi}	111.24 ^{h}	27.04^{cd}	41.10^{e}	1.62^{d}

*Figures not sharing the same letters in the same column differ significantly at $p<0.05$

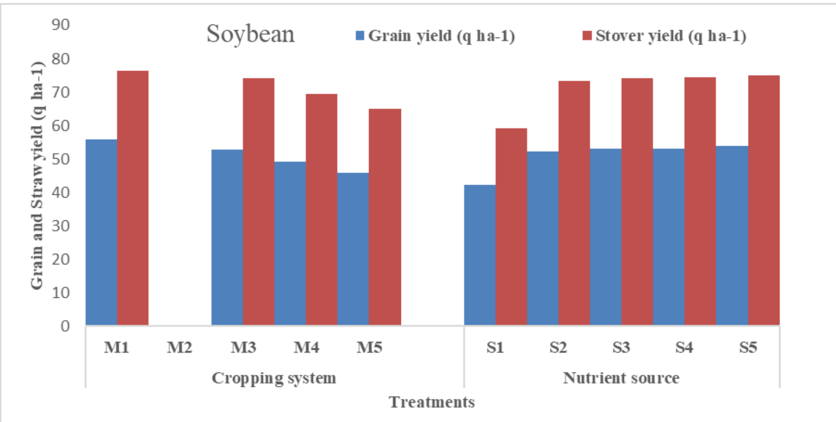

Fig. 3. Graphical representation of grain and straw yield of soybean

Moreover, the benefits observed in this study can be ascribed to optimized planting patterns and improved resource utilization during the co-growth period of the crops. Ghosh (2004) also noted that higher LER values correlate with significant economic benefits, as indicated by maximum monetary advantage values (36).

***Nutrient management effect*:** The maize equivalent yield exhibited significant variation across different nutrient management practices. The highest MEY was recorded for the plant extract NPK treatment at 89.26 q ha^{-1}, which was statistically comparable to the MEY under the application of 70% recommended dose of fertilizers combined with a homemade NPK fertilizer spray at 87.46 q ha^{-1}. The elevated MEY can be attributed to the presence of bioactive compounds that enhance overall plant vigor and stress resistance, promoting root development and nutrient uptake (35). Nano fertilizers positively influence plant physiology by increasing root biomass, thereby enhancing the efficiency of nutrient absorption from the soil rhizosphere. This improvement in nutrient acquisition subsequently has beneficial effects on yield attributes and overall yield (27-28). A similar trend was observed for soybean equivalent yield, with statistically significant differences noted among the treatment groups. The SEY for the NPK treatment, which was comparable to that of the 70% RDF supplemented with the custom-made NPK spray, demonstrated an increase of 28.39% to 19.4% compared to the control treatment.

***Interaction effect*:** The interaction effect of maize-soybean intercropping at a 1:1 ratio, coupled with foliar application of NPK plant extract, achieved the highest marketable economic yield of 100.48 q ha^{-1} and seed economic yield of 45.69 q ha^{-1}. Conversely, the control group exhibited the lowest marketable economic yield of 55.77 q ha^{-1} and seed economic yield of 22.36 q ha^{-1}. This intercropping system demonstrated a significant positive synergistic effect, enhancing nutrient uptake and plant health through the bioactive compounds present in the plant extracts (40). The efficacy of the foliar application of plant extracts was comparable to that of homemade NPK and nano NPK sprays. Additionally, these foliar applications, including homemade NPK and nano NPK, can enhance nutrient utilization efficiency by up to three times compared to conventional fertilizers, facilitating a steady release of essential nutrients (38).

Conclusion

The current study demonstrates that both planting geometry and nutrient management practices significantly influence the growth and yield of maize within a maize-soybean cropping system. Sole cropping of maize consistently yielded superior results compared to intercropping, exhibiting greater plant height, leaf area, crop growth rate (CGR), grain yield and stover yield. This advantage can be attributed to reduced competition for light, water and nutrients in monoculture systems. Among the various nutrient management strategies assessed, the foliar application of NPK derived from plant extracts resulted in the highest yields, followed closely by nano NPK and homemade NPK sprays. These fertilizers enhance nutrient availability and contain bioactive compounds that promote plant vigor and stress resilience. The highest crop equivalent yield and land equivalent ratio were achieved in the maize-soybean intercropping system at a 1:1 ratio, indicating optimal resource utilization. This study underscores the significance of optimized nutrient management and planting configurations in maximizing maize productivity. Such strategies not only enhance land productivity but also improve nitrogen use efficiency, which is critical for advancing sustainable agricultural practices. Overall, the findings suggest that mono-cropping, when combined with advanced nutrient applications, can substantially enhance yield outcomes.

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Authors' contributions

UKS conceived and conducted the research and data analysis. SK supervised the research project. Review and editing drafts, analysis, original draft writing, software facility and visualization are done by SK, PV and BB. All the authors read and approved the final manuscript

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None.

References

1. Godfray HCJ, Beddington JR, Crute IR, Haddad L, et al. Food security: The challenge of feeding 9 billion people. Science. 2010;327(5967):812-18.
2. Foley JA, Ramankutty N, Brauman KA, Cassidy ES, et al. Solutions for a cultivated planet. Nature. 2011;478(7369):337-42.
3. Katyayan A. Fundamentals of agriculture. Varanasi, Uttar Pradesh: Kushal Publications and Distributors. 2005;p. 10-1.
4. Lithourgidis AS, Dordas CA, Damalas CA, Vlachostergios D. Annual intercrops: an alternative pathway for sustainable agriculture. Aust J Crop Sci. 2011;5(4):396-410.
5. Ghanbari A, Dahmardeh M, Siahsar BA, Ramroudi M. Effect of maize (*Zea mays* L.) - cowpea (*Vigna unguiculata* L.) intercropping on light distribution, soil temperature and soil moisture in arid environment. J Food Agric Environ. 2010;8:102-08. https://www.cabidigitallibrary.org/doi/full/10.5555/20103048861
6. Prasad R, Brook R. Effect of varying maize densities on intercropped maize and soybean in Nepal. Exp Agric. 2005;41(3):365-82. https://doi.org/10.1017/S0014479705002693
7. Manna M, Ghosh P, Acharya C. Sustainable crop production through management of soil organic carbon in semiarid and tropical India. J Sustain Agric. 2003;21(3):85-114. https://doi.org/10.1300/J064v21n03_07

8. Kocsy G, Toth B, Berzy T, Szalai G, et al. Glutathione reductase activity and chilling tolerance are induced by a hydroxylamine derivative BRX-156 in maize and soybean. Plant Sci. 2001;160 (5):943-50. https://doi.org/10.1016/S0168-9452(01)00333-8

9. FAO. FAO statistical yearbook: World food and agriculture. Rome: FAO; 2020.

10. Directorate of maize research. ICAR-Indian Institute of Maize Research; 2024. https://iimr.icar.gov.in

11. Battaglia M, Thomason W, Fike J, Evanylo G, von Cossel M, Babur E. The broad impacts of corn stover and wheat straw removal for biofuel production on crop productivity, soil health and greenhouse gases emissions - A review. GCB Bioenergy. 2021;13(1):45-57. https://doi.org/10.1111/gcbb.12774

12. Liu Y, Du H, Li P, Shen Y, et al. Pan-genome of wild and cultivated soybeans. Cell. 2020;182(1):162-76. https://doi.org/10.1016/j.cell.2020.05.023

13. Yang F, Huang S, Gao R, Liu W, et al. Growth of soybean seedlings in relay strip intercropping systems in relation to light quantity and red: Far-red ratio. Field Crops Res. 2014;155:245-53. https://doi.org/10.1016/j.fcr.2013.08.011

14. Valinejad M, Vaseghi S, Afzali M. Starter nitrogen fertilizer impact on soybean yield and quality. Int J Eng Adv Technol. 2013;3(1):333-37.

15. Mustafa M, Azam M, Bhatti HN, Khan A, et al. Green fabrication of copper nano-fertilizer for enhanced crop yield in cowpea cultivar: A sustainable approach. Biocatalysis and Agricultural Biotechnology. 2024;56. https://doi.org/10.1016/j.bcab.2023.102994

16. Mkindi AG, Tembo YL, Mbega ER, Smith AK, et al. Extracts of common pesticidal plants increase plant growth and yield in common bean plants. Plants. 2020;9(2):149.

17. Keya Tudu C, Dey A, Pandey DK, Panwar JS, Nandy S. Role of plant derived extracts as biostimulants in sustainable agriculture: A detailed study on research advances, bottlenecks and future prospects. New and Future Developments in Microbial Biotechnology and Bioengineering. 2022;159-79.

18. Gomez KA, Gomez AA. Statistical Procedures for Agricultural Research. 2nd Edition, John Wiley and Sons, New York. 1984;680.

19. Usman M, Nangere MG, Musa I. Effect of three levels of NPK fertilizer on growth parameters and yield of maize-soybean intercrop. Int J Sci Res Publ. 2015;5(9):1-6. https://doi.org/d41edd4b9faf1981acac227c8d2565b19c4354

20. DeRosa MC, Monreal C, Schnitzer M, Walsh R, Sultan Y. Nanotechnology in fertilizers. Nat Nanotechnol. 2010;5(2):91-93. https://www.nature.com/articles/nnano.2010.2

21. Al-Zreejawi SA, Al-Juthery H. Effect of spray with nano NPK, complete micro fertilizers and nano amino acids on some growth and yield indicators of maize (*Zea mays* L.). IOP Conf Ser Earth Environ Sci. 2020;9(1):553.

22. Si Z, Qin A, Liang Y, Duan A, Gao Y. A review on regulation of irrigation management on wheat physiology, grain yield and quality. Plants (Basel). 2023;12(4):692. https://www.mdpi.com/2223-7747/12/4/692

23. Raza MA, Feng LY, van der Werf W, Cai GR, et al. Narrow-wide-row planting pattern increases the radiation use efficiency and seed yield of intercrop species in relay-intercropping system. Food Energy Secur. 2019;8(3). https://doi.org/10.1002/fes3.170.

24. Manasa P, Maitra S, Barman S. Yield attributes, yield, competitive ability and economics of summer maize-legume intercropping system. Int J Agric Environ Biotechnol. 2020;13(1):33-38. https://doi.org/10.30954/0974-1712.1.2020.16

25. Rajeshkumar A, Venkataraman NS, Ramadass S. Integrated weed management in maize-based intercropping systems. Indian J Weed Sci. 2018;50(1):79-81. https://doi.org/10.5958/0974-8164.2018.00018.7

26. Twaij BM, Hasan MN. Bioactive secondary metabolites from plant sources: Types, synthesis and their therapeutic uses. Int J Plant Biol. 2022;13(1):4-14. https://doi.org/10.3390/ijpb13010003

27. Rajendran M, Selvaraj RCA, Sundaram VB. Evaluation of nanostructured slow-release fertilizer on soil fertility, yield and nutritional profile of *Vigna radiata*. Recent Pat Nanotechnol. 2017;11(1):1-13.

28. Rashmi CM, Prakash SS. Effect of nano phosphorus fertilizers on growth and yield of maize (*Zea mays* L.) in central dry zone of Karnataka. Mysore J Agric Sci. 2023;57(2):286-93. Available from: http://uasbangalore.edu.in

29. Abdel-Aziz HMM, Hasaneen MNA, Omer AM. Nano chitosan-NPK fertilizer enhances the growth and productivity of wheat plants grown in sandy soil. Span J Agric Res. 2016;14 (1):902-10. https://doi.org/10.5424/sjar/2016141-8205

30. Babubhai BD. Evaluation of potassic nano fertilizer under incubation trial and its effect on growth, yield and nutrient uptake by maize (*Zea mays* L.) crop [MSc thesis]. Junagadh: Junagadh Agriculture University; 2018.

31. Rathnayaka RMNN, Mahendran S, Iqbal YB, Rifnas LM. Influence of urea and nano-nitrogen fertilizers on the growth and yield of rice (*Oryza sativa* L.) cultivar 'Bg 250'. Int J Res Pub. 2018;5(2):1-9. https://hal.science/hal-04194488

32. Mandal MK, Banerjee M, Banerjee H, Alipatra A, Malik GC. Productivity of maize (*Zea mays*) based intercropping system during kharif season under red and lateritic tract of West Bengal. Bioscan. 2014;9(1):31-35. https://links/5715058208aeafcb935d29e3

33. Raza MA, Khalid MHB, Zhang X, Feng LY, et al. Effect of planting patterns on yield, nutrient accumulation and distribution in maize and soybean under relay intercropping systems. Sci Rep. 2019;9(1):4947. https://www.nature.com/articles/s41598-019-41364-1

34. Yang F, Wang X, Liao D, Lu F, Gao R, et al. Yield response to different planting geometries in maize-soybean relay strip intercropping systems. Agron J. 2015;107(1):296-304. https://doi.org/10.2134/agronj14.0263

35. Avil Kumar K, Reddy MD, Sivasankar A, Reddy NV. Yield and economics of maize (*Zea mays*) and soybean (*Glycine max*) in intercropping under different row proportion. Indian J Agric Sci. 2003;73(2):69-71.

36. Ghosh P. Growth, yield, competition and economics of groundnut/cereal fodder intercropping systems in the semi-arid tropics of India. Field Crops Res. 2004;88(2-3):227-37. https://doi.org/10.1016/j.fcr.2004.01.015

37. Nardi S, Pizzeghello D, Schiavon M, Ertani A. Plant biostimulants physiological responses induced by protein hydrolyzed-based products and humic substances in plant metabolism. Scientia Agricola. 2016;73(1):18-23. https://doi.org/10.1590/0103-9016-2015-0006.

38. Iqbal M, Umar S, Mahmooduzzafar F. Nano-fertilization to enhance nutrient use efficiency and productivity of crop plants. Nanomaterials and Plant Potential. 2019;473-505.

39. Rawat S, Singh RK, Singh P, Upadhyay PK, et al. Studies on comparison of nano-urea and prilled urea for enhancing maize (*Zea mays*) growth and productivity. Indian J Agric Sci. 2024;94 (3):325-28. https://doi.org/10.56093/ijas.v94i3.143292

40. Kumar R, Kumar S, Chikkappa GK, Das AK, et al. Unveiling genotype × environment dynamics for grain yield in QPM hybrids through AMMI, GGE Biplot and MTSI approach. Indian J Genet. 2024;84(3):449-60.