Natural Resources, 2024, 15, 189-210
https://www.scirp.org/journal/nr
ISSN Online: 2158-7086
ISSN Print: 2158-706X

Assessing the Influence of Phosphorus Fertilization on the Growth and Yield of Maize/Soybean Intercrop by Analyzing Nitrogen Uptake

Bertha Magombo[1], Chunjie Li[1], Benjamin Kolie[2,3]

[1]Department of Resource and Environmental Science, and Plant Protection, China Agricultural University, Beijing, China
[2]Institute of Geographic Sciences and Natural Resources Research, Chinese Academic of Science, Beijing, China
[3]Department of Resources and Environmental Management, University of the Chinese Academy of Sciences, Beijing, China
Email: berthamagombo21@gmail.com, leechunjie@126.com, bkolie2021@igsnrr.ac.cn

How to cite this paper: Magombo, B., Li, C.J. and Kolie, B. (2024) Assessing the Influence of Phosphorus Fertilization on the Growth and Yield of Maize/Soybean Intercrop by Analyzing Nitrogen Uptake. *Natural Resources*, **15**, 189-210.
https://doi.org/ 10.4236/nr.2024.158013

Received: June 29, 2024
Accepted: July 29, 2024
Published: August 1, 2024

Abstract

Intercropping, particularly the combination of maize and soybeans, has been widely recognized for its potential to improve nitrogen uptake and promote sustainable agriculture. This study examines the patterns of nitrogen uptake in maize and soybean intercropping systems under different growth stages and phosphorus fertilization levels and investigates the influence of nitrogen uptake on growth parameters such as plant height, leaf area, and biomass accumulation in the maize/soybean intercrop under different phosphorus fertilization regimes. The study also collected chlorophyll samples at different growth stages of maize in monoculture and intercropping with maize or soybean. The results showed that plant height was greater in V10 in both fertilized and unfertilized treatments for intercropped maize and soybean, and chlorophyll concentration was higher in VT intercropped maize. The results also showed a higher accumulation of biomass. Understanding the growth dynamics of these plants in monoculture and intercropping systems and the impact of fertilization practices is crucial for optimizing crop productivity and sustainability in agricultural systems.

Keywords

Intercropping, Fertilization, Chlorophyll, Maize/Soybeans, Nitrogen

1. Introduction

Intercropping maize and soybeans are a widespread agricultural practice that aims to optimize land use and improve crop yields [1] [2]. This approach often involves the strategic application of fertilizers, particularly nitrogen (N) and phosphorus (P), to increase plant growth and productivity [3]. Phosphorus fertilization is a critical factor in agricultural systems as it is essential for various plant processes, including energy transfer, photosynthesis, and nutrient transport [3]. However, the effects of P fertilization on the growth and yield of maize/soybean intercrops, especially in terms of N uptake, are complex and require in-depth investigation [4]. Studies have shown that while N fertilization significantly affects maize growth parameters and forage quality, P fertilization does not always have a similar effect on growth characteristics or dry matter yield [5]. In contrast, P fertilization can improve N fixation in legumes, which indirectly benefits intercropped maize by improving grain quality, despite not increasing yield [6]. Furthermore, the interaction between N and P fertilization and plant population density can affect the yield and protein content of intercropped maize and soybeans [7]. The balance between maize and soybean development in intercropping systems can be influenced by varying N levels and plant densities, with implications for biomass yield and silage crude protein yield [8]. The role of P fertilization in maize/soybean intercrops extends beyond direct effects on yield. It can interact with other agronomic practices, such as straw mulching, to influence plant growth, nitrogen uptake, and photosynthetic efficiency, ultimately affecting crop yield [9]. Additionally, the arrangement of maize and soybean plants in intercropping systems can impact forage yield, silage quality, and grain yield, with certain row arrangements optimizing crude protein yield per area [10]. The environmental sustainability of these systems, including their global warming potential and carbon sequestration capacity, is also influenced by N and P fertilization rates [1]. Alternative fertilization strategies, such as using poultry manure combined with mineral fertilizers, have been shown to enhance growth and yield parameters in maize/soybean intercrops [11]. Moreover, the incorporation of biological agents like Brady rhizobium inoculants can improve N fixation and productivity in these systems [12]. Lastly, the residual effects of fertility amendments, such as rice mill ash, on soil productivity and crop yield components in maize/soybean intercrops highlight the importance of long-term soil fertility management [6].

Phosphorus fertilization impacts the availability of nutrients in the soil [13]. Investigating the relationship between phosphorus fertilization and nitrogen uptake in maize/soybean intercropping can reveal synergistic effects that shed light on how these nutrients collectively influence crop performance [14]. The quantification of nitrogen uptake efficiency in maize/soybean intercropping has provided vital insights into sustainable agriculture in China and has the potential to be applied in other regions, such as Africa [15]. Understanding the mechanisms driving nitrogen uptake efficiency in intercropping systems is crucial for developing sustainable farming practices globally [1]. Examining the dynamics of nitrogen fixation, uptake, and leaching at various soil depths in maize/bean intercropping systems that receive phosphorus fertilization offers a comprehensive perspective on nutrient management in these agricultural contexts [16]. The combination of maize (*Zea mays*) and soybean (*Glycine max*) in the intercropping system has garnered attention for its potential to enhance nutrient utilization and overall crop performance [17].

The impact of phosphorus fertilization on maize/soybean intercrops is multifaceted, influencing growth and yield, nitrogen uptake, photosynthesis, and environmental sustainability. The interaction between phosphorus fertilization and other agronomic practices, as well as the choice of fertilization strategy, plays a crucial role in determining the overall success of maize/soybean intercropping systems. Further research is needed to optimize fertilizer use in these systems for enhanced productivity and environmental benefits [4] [9] [16] [18].

The main objectives of this study are 1) to investigate the patterns of nitrogen uptake in maize and soybean intercrop systems at different growth stages and phosphorus fertilization levels and 2) to evaluate the effects of nitrogen uptake on maize-soybean intercrop growth parameters, such as plant height, leaf area, and biomass accumulation, under different phosphorus fertilization regimes. In addition, the study aims 3) to understand how nitrogen availability, which is influenced by phosphorus fertilization, affects yield components such as grain weight, pod formation, and overall productivity of the maize/soybean intercrop. This research has the potential to improve the understanding of nitrogen utilization in intercropping systems and provide practical insights for optimizing phosphorus fertilization strategies to improve the efficiency of nitrogen uptake in maize/soybean intercrops [19]. Investigating the effects of nitrogen uptake on crop productivity can inform farmers and policymakers of the potential economic and environmental benefits of reducing external nitrogen inputs via intercropping practices [4]. Maize/soybean intercropping, in particular, has immense potential to revolutionize nutrient management in agricultural systems [20], and the insights gained from this research can play a crucial role in advancing sustainable farming practices not only in China but also in other regions facing similar agricultural challenges [21].

2. Literature Review

Intercropping, the practice of cultivating multiple crop species in the same field, has garnered significant attention in recent years because of its potential to boost crop productivity, resource-use efficiency, and soil health [22]. Phosphorus (P) is a vital nutrient for plant growth, playing a pivotal role in various metabolic processes, including energy transfer, photosynthesis, and nutrient uptake. Adequate P supply is particularly critical for leguminous crops, such as soybeans, which have a high demand for P to support nitrogen fixation and protein synthesis [23]. Maize, on the other hand, is a substantial consumer of nitrogen (N), requiring considerable amounts of N for vegetative growth and grain production.

An extensive body of research has explored the effects of phosphorus fertilization on the growth and yield of maize and soybean crops grown in intercropping systems. These studies have demonstrated that P fertilization can significantly enhance crop growth, yield, and nutrient uptake in intercropped systems [24]. Specifically, P fertilization has been shown to improve root growth, nutrient uptake efficiency, and photosynthetic capacity in maize and soybean intercrops [25]. The impact of phosphorus fertilization on crop growth and yield in intercropping systems depends on nitrogen uptake. Nitrogen is a vital nutrient for plant development and is necessary for the synthesis of proteins, nucleic acids, and chlorophyll [16]. In intercropping systems, nitrogen uptake can be affected by various factors, including phosphorus availability, soil nutrient status, and crop species interactions.

Several studies have shown that phosphorus fertilization can increase nitrogen uptake and utilization efficiency in maize and soybean intercrops [18] [21] [26]. For instance, research has indicated that P application can enhance the activity of nitrogen-fixing rhizobia in soybean roots, leading to improved nitrogen fixation and plant growth. Similarly, phosphorus fertilization has been found to increase nitrogen uptake and translocation in maize plants, resulting in increased grain yield and protein content [27].

Overall, the literature suggests that phosphorus fertilization plays a critical role in improving crop growth, yield, and nitrogen uptake in maize/soybean intercropping systems. Further research is needed to investigate the underlying mechanisms of the interactive effects of phosphorus and nitrogen on crop performance and to develop sustainable management practices to optimize nutrient use efficiency and crop productivity in intercropping systems.

3. Methods and Materials

3.1. Experimental Site and Method

The experiment was conducted from June to October 2023 at the Quzhou experimental station of China Agricultural University, which is situated in the North China Plain of Hebei Province at a latitude of, 1150E, 36.50N, and an elevation of 37 m above sea level. The trial was carried out during the short growing season from 15 June to 03 October 2023. The dimensions of each plot were 8 m × 9 m in size for both monoculture and intercropped maize/soybean. Maize and soybeans were harvested after 110 days of planting. The study was conducted using a randomized block-split plot design, the main plot was divided into three cropping systems. The trial included two phosphorus treatments: one without P application (P0) and the other with a P application of 80 kg P_2O_5 per ha. Crop treatments included (1) maize alone, (2) soybean alone, and (3) soybean/maize intercropping, a maize/soybean intercrop with paired legume rows between two maize rows or two paired legume rows.

Plant Material

The vegetative materials used were one of the varieties of quality maize (MC812) and one variety of soybean (Jidou12). The two materials were chosen for their yield potential availability of seeds to users and breeders and also food preferences.

3.2. Data Collection

Plant height samples were collected at various growth stages of maize and soybeans. The samples were collected at different growth stages namely V7, V10, VT, and R1 for maize in monoculture and intercropped with maize, and also at V2, V3, R1, and R3 growth stages for monoculture soybean and intercropped soybean (Nasar *et al.* 2023). The growth stages of maize were classified as either vegetative (V) or reproductive (R). Three maize plants were selected randomly in each field and an average value was obtained both in monoculture and intercropped fields at different stages [28], much focus was on V7 and V10, because these two stages are the most critical in maize, and long tape was used when measuring this height. The height was measured from the base of the plant to the tip of the tallest leaf [29].

Chlorophyll data were collected at weekly intervals throughout the study period. Chlorophyll content was quantified using a SPAD meter, a device that measures chlorophyll levels on the leaf surface [30]. To obtain accurate readings, three random areas of each leaf were selected and measured with the SPAD meter placed on the leaf surface, and the readings were recorded. The average of the measurements was then calculated to determine the chlorophyll content for each time point [31]. Particularly important for chlorophyll content were certain growth stages during the period of data collection. These critical growth stages included V7 (7 visible leaf collars), VT (tasselling stage), V10 (10 visible leaf collars) and R1 (silking stage). Understanding the variations in chlorophyll content at these specific growth stages provides valuable insight into the physiological development of maize plants and can help optimize agricultural practices data for chlorophyll was collected every seven days. The chlorophyll content was determined using SPAD, which measures the leaf surface [32]. Three random parts of each leaf were selected and measured using the SPAD meter, the SPAD meter was placed on the leaf surface and recorded in the reading. The average value was then obtained. The actual growth stages that were much emphasized in chlorophyll during the data collection were V7, VT, V10, and R1.

Plant girth samples were methodically obtained by randomly selecting three maize plant stems within the field setting and employing a caliper tool for circumference measurement [33]. The standard protocol for measuring maize girth involved selecting the measurement point at a height ranging between 10 - 15 cm above the ground level to ensure uniformity and accuracy across samples. This meticulous approach aimed to capture the variations in stem diameter growth and development, which is indicative of the plant's overall health and vigor [34].

Leaf area samples were systematically collected by randomly selecting three maize leaves in the field during the pivotal growth stages of V7 and V10. A measuring tape was utilized to measure the surface area of each selected leaf, ensuring accuracy and consistency in the data collection process [35]. The measurements were taken to gain insights into the leaf development and growth dynamics of the maize plants at these critical stages. By obtaining the average leaf area value Leaf area samples were collected by randomly selecting three maize leaves in the field and measuring the area using a measuring tape during the V7 and V10 growth stages. The average value was obtained.

3.3. Statistical Analyses

The statistical analysis of all the measured factors was carried out using the Analysis of variance (ANOVA) on the Statistical Package for the Social Sciences (SPSS) and sigma plot version 2020, while Microsoft Excel was utilized to organize the data in the form of tables. Origin Pro 2022b was employed for graphical representation.

4. Results

4.1. Chlorophyll Response in Maize Intercrop under Phosphorus Fertilization

Based on the data collected from the intercropped maize, there was a significant difference in the concentration of chlorophyll between monoculture and intercropping in fertilized and non-fertilized treatments at the VT stage ($P < 0.05$), as shown in **Figure 1(a)**. However, the intercropped maize with fertilized treatment had a consistently higher concentration of chlorophyll from VT to R1 as observed in the field [36]. These findings suggest that the maize crop in the non-fertilized treatment experienced delayed drying compared to the fertilized treatment.

Furthermore, the outcomes from the soybean intercropped system demonstrate that the chlorophyll concentration in the intercropped maize in non-fertilized treatment was consistently greater than in the monoculture maize non-fertilized treatment at all stages [8], as depicted in **Figure 1(b)**. Moreover, the data revealed a significant increase in chlorophyll content from the VT stage in the intercropped soybean in the non-fertilized treatment compared to the monoculture maize non-fertilized treatment, as shown in **Figure 1(c)**. This indicates that the maize in the fertilized treatment was actively engaged in the photosynthesis process which resulted in a higher concentration of chlorophyll [31].

4.2. Chlorophyll Response in Sole Soybean and Soybeans Intercrop under Phosphorus Fertilization

The results of the intercropped soybeans revealed a higher chlorophyll concentration at the R1 growth stage in both the fertilized and non-fertilized treatments in intercropped soybeans [37], as depicted in **Figure 2(a)**. Nevertheless, both treatments remained relatively low at the V3 and R3 growth stages in monoculture

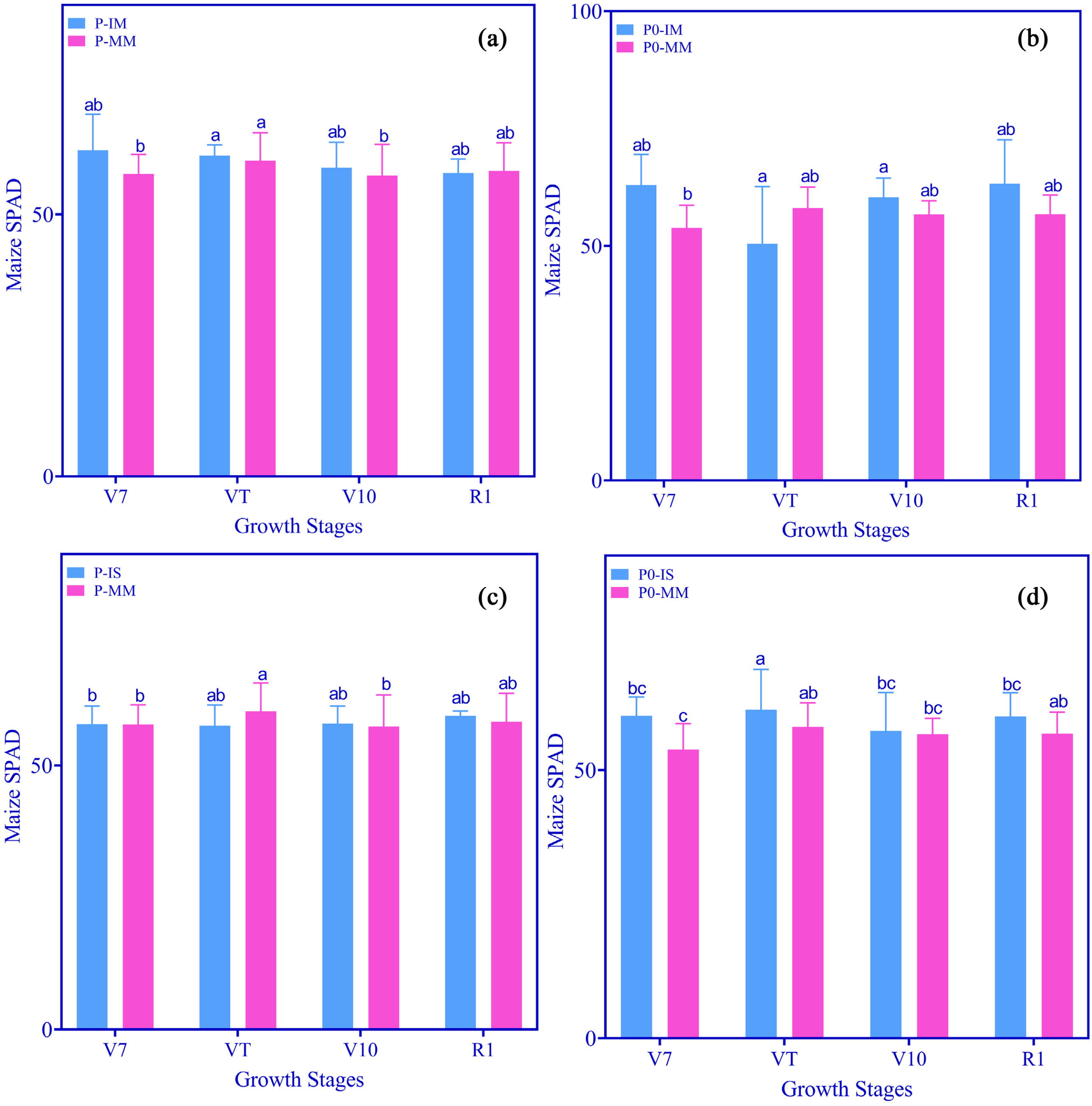

Figure 1. Chlorophyll response in maize intercrop under Phosphorus fertilization in sole and intercrop. P-IS (intercropped soybean), P-MM (monoculture maize), and P-IM (intercropped maize). P: Fertilized, P0: non-P-fertilized.

soybean as illustrated in Figure 2(b) and Figure 2(c). In comparing maize-soybean intercropping and mono-cropping systems, it was observed that the chlorophyll concentration in soybean was relatively higher in intercropped soybean than in monoculture in all the treatments [8].

4.3. Girth Response under Phosphorus Fertilizer in Mono-Cropped and Intercropped Maize

The stem diameter of intercropped maize at the V7 stage was comparable to that

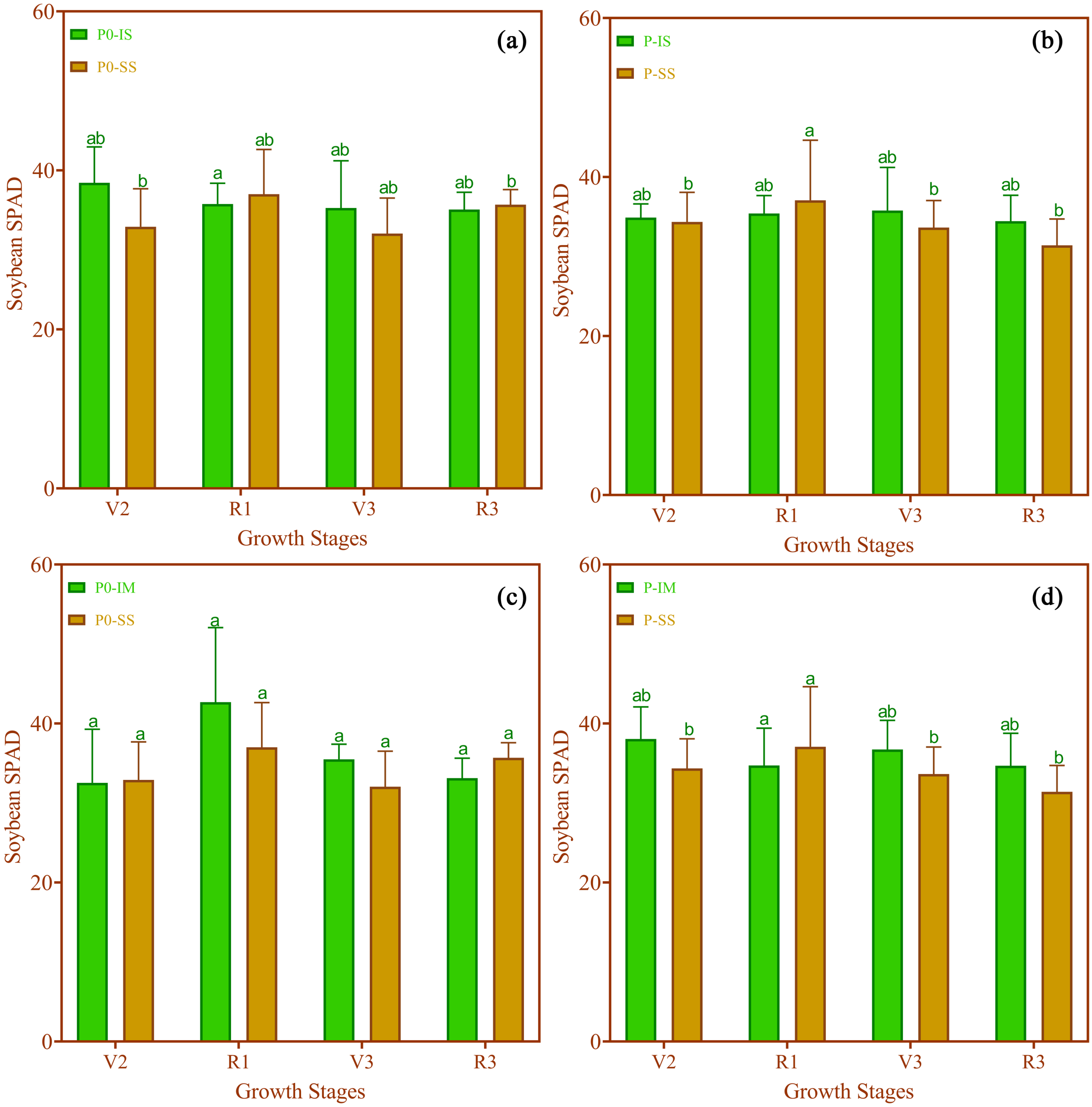

Figure 2. Chlorophyll response in soybean, sole and intercropped maize, and soybean under Phosphorus fertilization; P-IS (intercropped soybean), P-MM (monoculture maize), P-IM (intercropped maize). P-SS (sole soybean); P (fertilized), P0 (non-P-fertilized).

of the maize monoculture at the V10 stage, where phosphorus fertilizer was not applied, as shown in **Figure 3(a)** and **Figure 3(b)**. Conversely, in **Figure 3(a)** and **Figure 3(b)**, where phosphorus fertilizer was applied, the stem diameter was higher at the V7 stage in sole maize in both treatments that are fertilized and non-fertilized, however, there was no significant difference between the stem diameters of the monoculture and the intercropping system.

The stem diameter of intercropped soybeans at the V7 and V10 growth stages, as depicted in **Figure 4(a)**, was nearly indistinguishable between the plots that

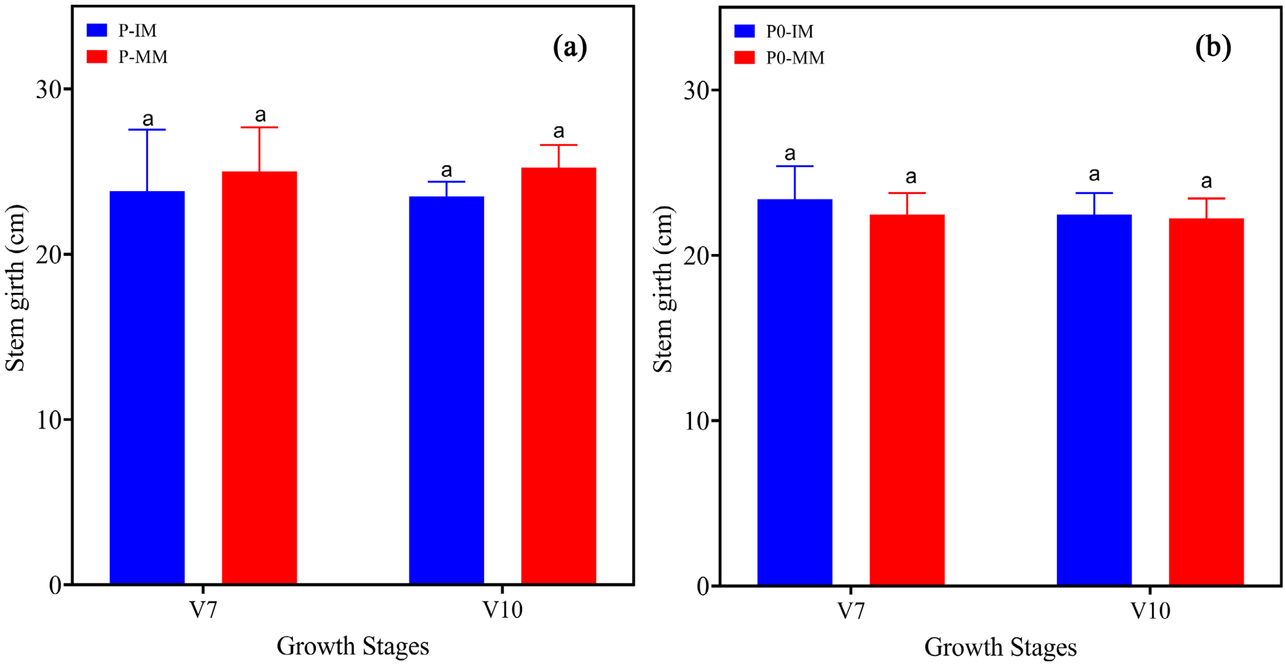

Figure 3. Girth response in intercropped maize under phosphorus fertilizer; P-IM (intercropped maize), P-MM (sole maize).

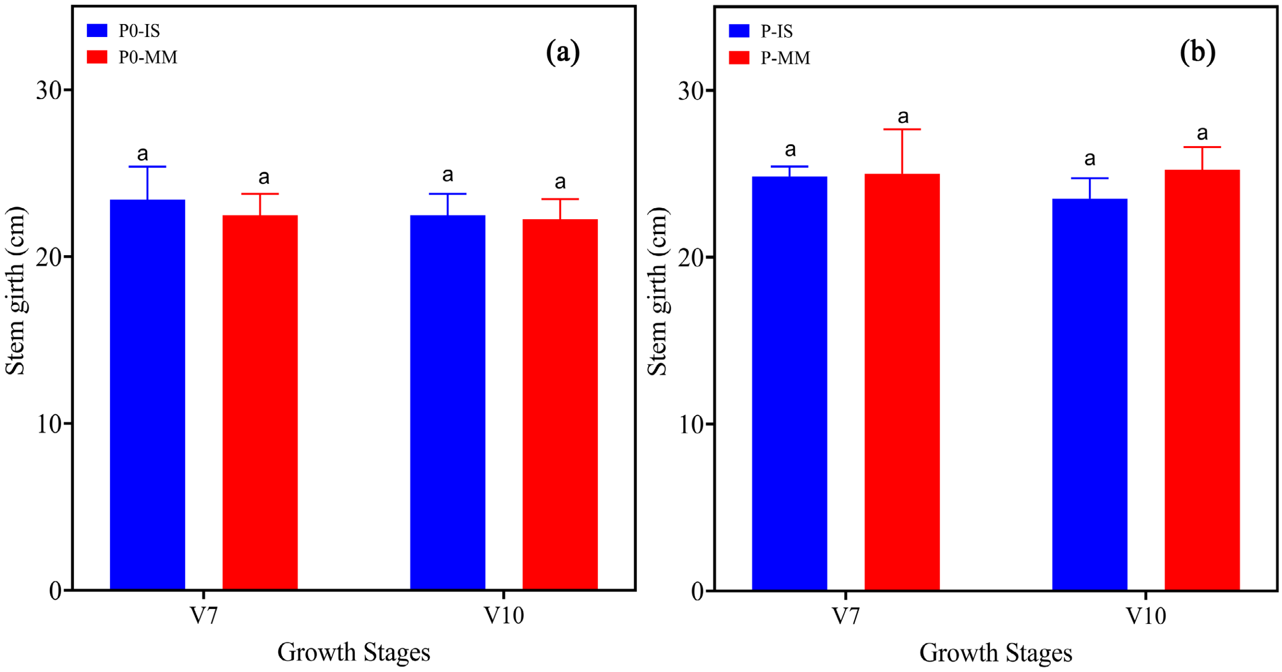

Figure 4. Girth response in intercropped soybean under phosphorus fertilizer; P-IS (intercropped soybean), P-MM (sole maize).

received phosphorus fertilizer and those that did not [11]. This suggests that there was no substantive difference between the two. The modest increase observed at V7 can be attributed to the nutrients naturally present in the soil, as well as the positive effect of the phosphorus fertilizer in promoting new cell growth and elongating existing cells, which ultimately contributes to the overall thickness and girth of the stem.

4.4. Plant Height Response in Monoculture and Intercropping Maize in V7 and V10 Growth Stage under Phosphorus Fertilizer

The findings demonstrated that plant growth in intercropped maize was greater at the V10 growth stage compared to the V7 growth stage in monoculture maize in all the treatments thus in fertilized and non-fertilized compared to intercropped maize [29], as depicted in **Figure 5(a)** and **Figure 5(b)**. At the V10 growth stage, there was increased growth in both fertilized and non-fertilized treatments, as shown in **Figure 5(b)**. When comparing the two Figures (**Figure 5(a)** and **Figure 5(b)**), it is

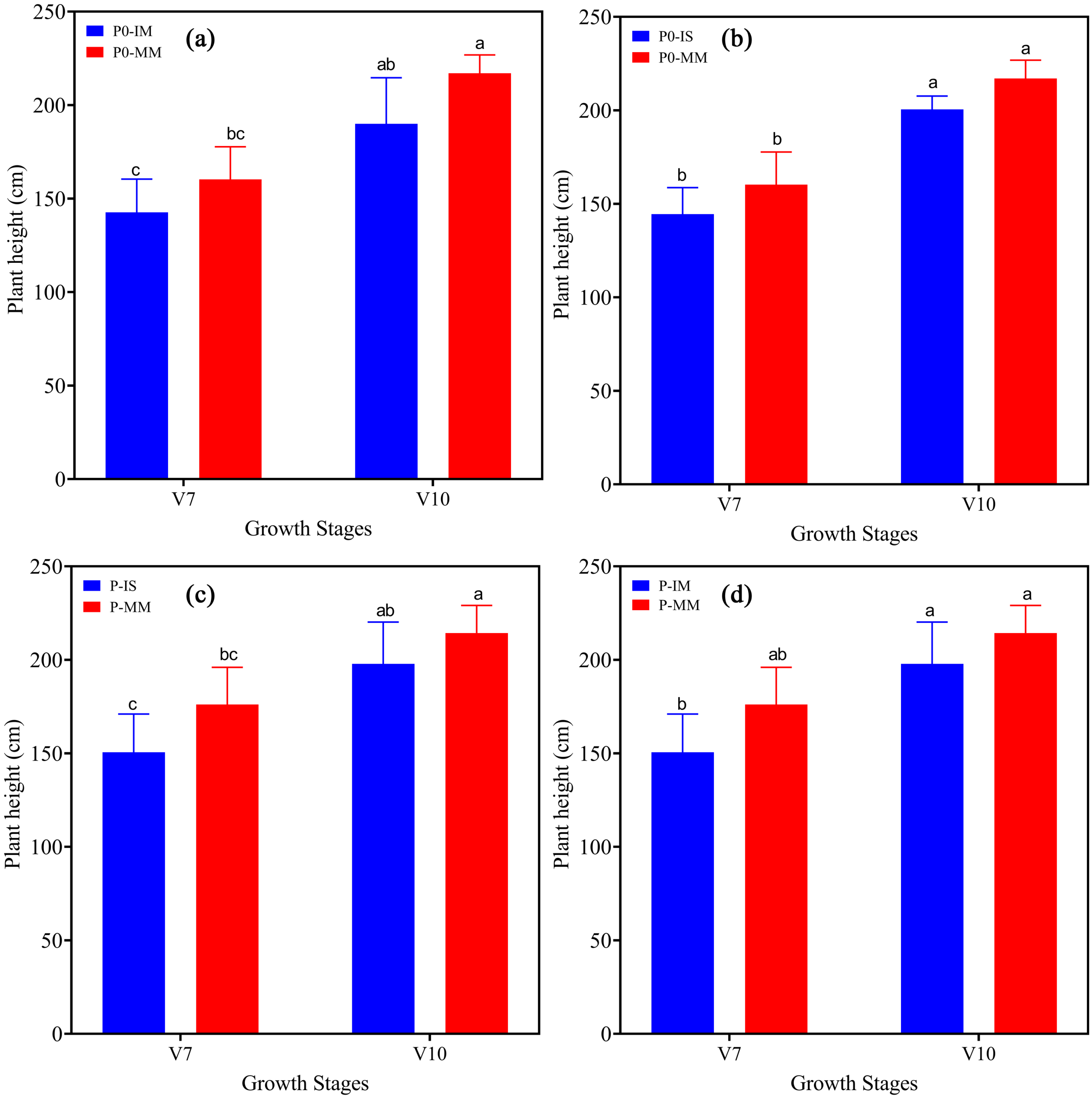

Figure 5. Plant height response in maize monoculture and intercropping under phosphorus fertilization; P-IM (intercropped maize), P-MM (sole maize), P (fertilized), P-0 (non-fertilized), P-IS (intercropped soybean).

evident that there was more growth at the V10 growth stage in both fertilized and non-fertilized treatments. However, the overall trend indicates that maize growth is more prevalent in monoculture plots than in intercropped plots [5], as shown in both fertilized and non-fertilized treatments, as depicted in **Figure 5(c)**.

4.5. Maize Grain Yield in Sole and Intercropped Maize under Fertilized and Non-Fertilized Treatments

Figure 6 presents the grain yield of maize in both monoculture and intercrop, with and without fertilization [28]. The results indicate that the grain yield in maize monoculture was lower under non-fertilized conditions compared to the maize intercrop without fertilizer, although there was no statistically significant difference between the two [22]. Similarly, the grain yield in monoculture maize with fertilized treatment was lower than in intercropped maize, but again, there was no statistically significant difference between the two treatments (Hidoto & Markos 2021).

4.6. Soybean Biomass in Sole and Intercropped Soybeans under Fertilized and Non-Fertilized Treatments

The results in **Figure 7** showed that the sole soybean biomass was greater at the R6 growth stage in both the sole and intercropped settings, with or without fertilizer application [38]. This may be attributed to the fact that at the R6 stage,

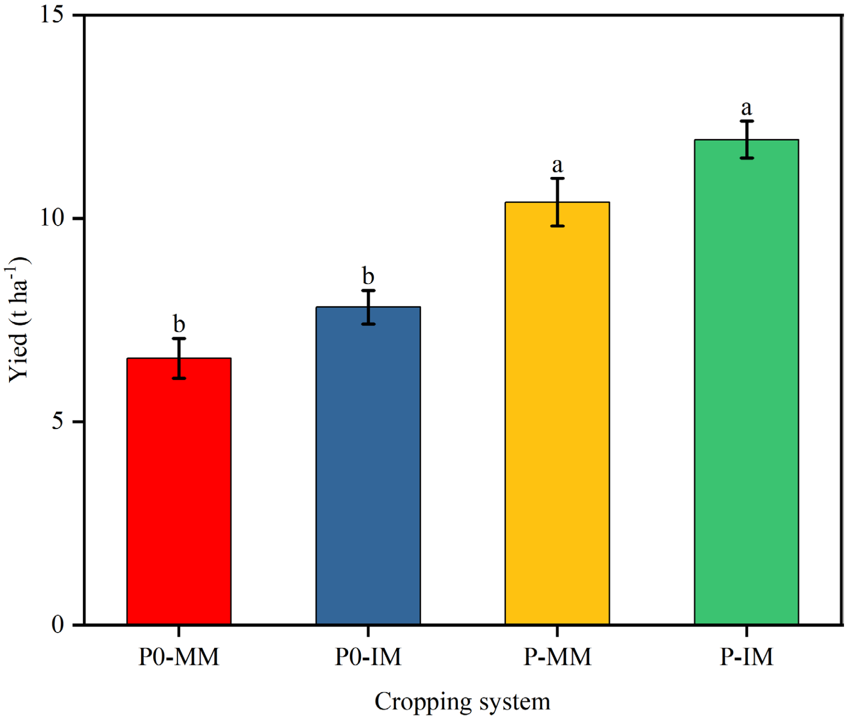

Figure 6. Grain yield for sole maize and intercropped maize; P-IM (intercropped maize thus maize/soybean), P-MM (sole maize), P (fertilized), P-0 (none fertilized), P-IS (intercropped soybean).

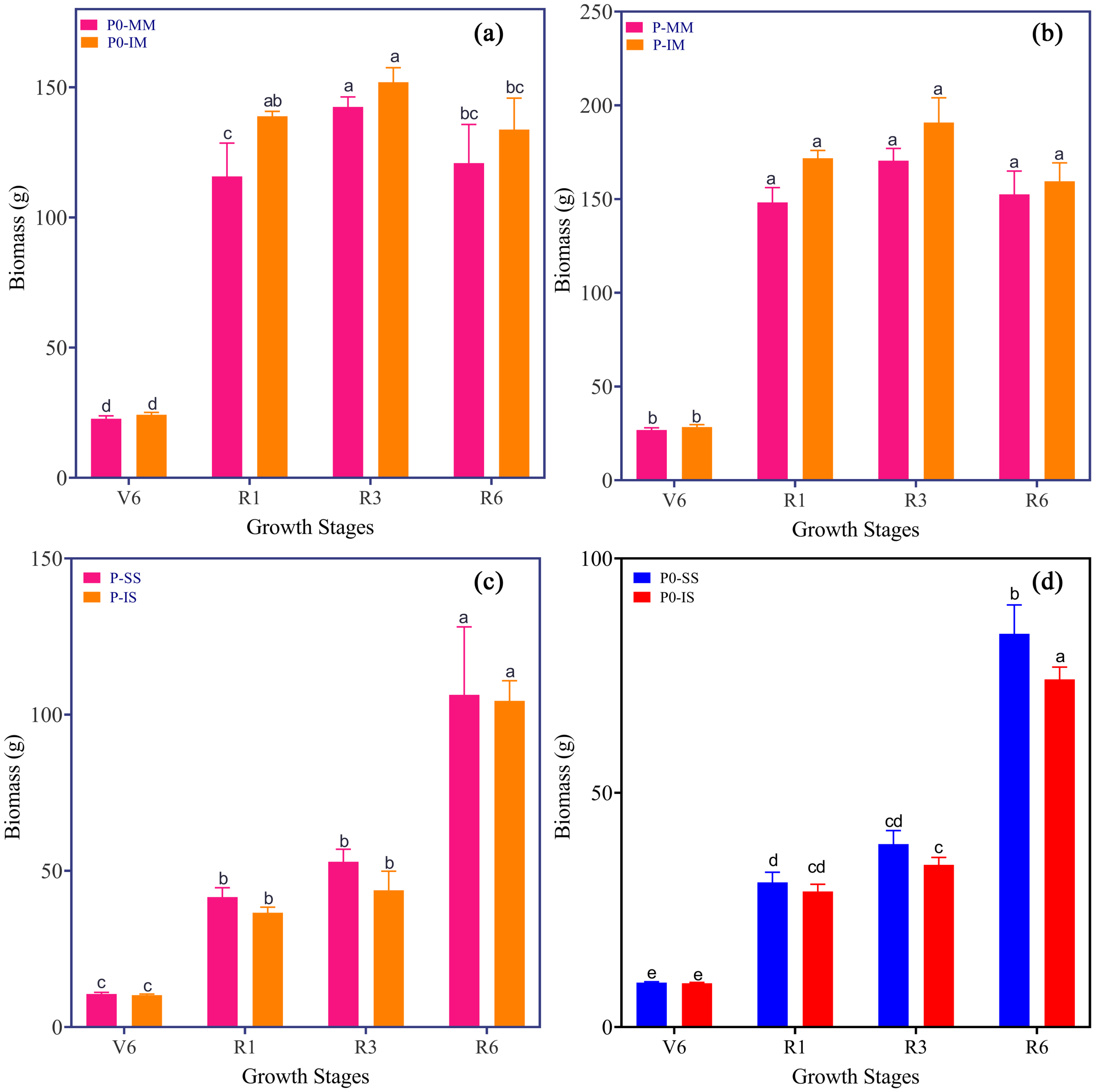

Figure 7. Biomass response phosphorus fertilizers under two cropping systems; P-MM (sole maize), P (fertilized), P-0 (non-fertilized).

plants are in a crucial reproductive phase where the demand for nutrients is higher to support pod development and seed filling [39]. Consequently, soybeans exhibit significant biomass production at this stage due to nitrogen fixation, irrespective of whether they are fertilized or not.

5. Discussion

5.1. Effect of Phosphorus on Plant Growth

The effects of phosphorus (P) fertilization on maize/soybean intercropping systems were investigated, focusing on growth, yield, and nitrogen (N) uptake. The studies paint a complex picture. Some report that P has no significant effect on maize yield [40]. While others find an improvement in crop quality and N fixation by legumes [41], the role of P in improving N uptake and fixation is also supported by the positive effects of farmyard manure, which likely provides P among other nutrients, on soil fertility and crop production in maize/soybean intercrops [16]. Contradictions arise when considering the effects of P fertilization on soybean yields. Some studies report higher yields in sole cropping compared to intercropping [42], while others suggest that intercropping systems can be optimized through specific planting patterns and row ratios to improve soil productivity and nutrient uptake [43]. In addition, the interaction of P with other agronomic practices, such as injection with Latati *et al.* (2018) and the use of rice mill ash [18], can significantly affect N fixation and yield. In summary, the effects of P fertilization on maize/soybean intercropping systems are diverse, with potential benefits for N uptake and fixation, plant quality, and yield. However, the effectiveness of P fertilization is influenced by several factors, including cropping patterns, soil fertility management, and the use of inoculants. Further research is needed to determine the optimal conditions under which P fertilization can maximize the benefits of maize/soybean intercropping systems.

5.2. Effect of the Phosphorus on Chlorophyll Concentration

Although there was a significant difference between the treatments, in intercropping, chlorophyll concentration was higher than in monoculture, due to the complementarity of resources, as maize and soybean have different root system structures and nutrient requirements [22]. Therefore, intercropping allows them to utilize different resources from the soil, such as nutrients and water, more efficiently than monoculture. This ensures better nutrient availability for chlorophyll synthesis, resulting in a higher chlorophyll concentration [31]. Intercropping increases biodiversity in the agroecosystem, which can promote positive interactions between plants and soil organisms [44]. This can lead to better nutrient cycling and nutrient availability, which further enhances chlorophyll production in intercropping systems, leading to higher chlorophyll concentration. Maize and soybean plants also have different canopy structures that allow for more effective light interception and utilization when intercropped. This improved light utilization can enhance photosynthesis efficiency, resulting in higher chlorophyll concentration [45].

5.3. Effect of the Phosphorus on Grain Yield

The grain yield of maize was lower in monoculture than in maize/soybean intercropping, which was higher. According to Hidoto and Markos 2021, efficient resource utilization Maize and soybeans have different root structures and nutrient requirements [25]. When grown in intercropping, they can use resources such as nutrients and water more efficiently. This efficient use of resources can lead to better overall plant growth and a higher grain yield than when maize is grown in monoculture. Another reason is complementarity, maize and soybean plants in a catch crop system can complement each other in terms of resource utilization [46]. For example, maize can benefit from the nitrogen-fixing capacity of soybeans, resulting in better nitrogen availability for maize growth. This complementarity can increase overall productivity and contribute to higher grain yields in the intercropping system [47]. Disease and pest control in intercropping can help reduce the incidence of pests and diseases by disrupting their host plants and habitats. This can lead to healthier maize plants with lower pest and disease pressure, ultimately contributing to higher grain yields compared to monoculture where pests and diseases may thrive more easily.

5.4. Monoculture and Intercrop Growth Patterns

The data in **Figures 5(a)-(c)** illustrate the variations in plant growth across the different stages of maize cultivation, specifically in monoculture and intercropping fields [48]. The findings indicate that the plant height was greater at the V10 stage in both fertilized and non-fertilized treatments for intercropped maize in **Figure 5(a)**, as well as in intercropped soybean and solitary maize [49]. This growth increase is particularly noticeable at the V10 stage, which is a pivotal phase for maize development, as it lays the groundwork for ear formation and grain production [50]. At this stage, the plants have fully developed leaves, are actively growing, and are transitioning from the vegetative stage to the reproductive stage. The roots are also well-established and efficiently absorb water and nutrients. The plant is simultaneously photosynthesizing and accumulating carbohydrates for reproductive growth, and its tassel and ear start to differentiate within the plant [11]. As a result, proper management during this stage is crucial to maximize yield potential. This practice of intercropping maize and soybean has gained considerable traction worldwide, particularly in regions like China, due to its double benefits of high productivity and simultaneous harvest of two distinct grains [17]. It is important to note that the application of phosphorus to the crop resulted in increased chlorophyll accumulation and enhanced maize stem girth. The results demonstrate the effective absorption of nitrogen when phosphorus is present, resulting in accelerated growth of maize in both stages, a crucial factor contributing to increased yield [51]. These findings align with prior research indicating that maize-soybean intercropping leads to higher yields due to greater nitrogen availability [52]. Nutrients are essential for plant growth, development, and overall health, with phosphorus playing a key role in facilitating the uptake and transportation of other essential nutrients, such as nitrogen [53]. This synergistic effect promotes efficient nutrient utilization for growth and development, explaining the higher plant growth observed at the V10 stage across all treatments, regardless of fertilization. Maize plants at the V10 stage typically exhibit vigorous growth and robust root development. Adequate phosphorus levels accelerate nitrogen uptake, fostering the development of healthy root systems capable of efficient water and nutrient absorption, leading to taller plants with dark green leaves and sturdy stalks, ultimately bolstering yield potential [54]. These findings align with previous observations of growth and yield patterns in cereal and legume intercropping systems [55]. Additionally, higher chlorophyll concentrations were observed at the VT growth stage in intercropped maize, indicating increased plant growth [56]. Chlorophyll, a pigment found in plant chloroplasts, plays a crucial role in photosynthesis, the process by which plants convert light energy into chemical energy (glucose) and oxygen. This process is essential for plant growth, as glucose serves as an energy source. Regarding stem girth, while there was no significant difference between treatments, maize/soybean intercropping displayed thicker stems at the V7 growth stage [35]. The stem serves as a vital organ supporting plant growth, development, and reproduction by providing structural support, facilitating the transportation of essential substances, contributing to photosynthesis, and storing nutrients [57].

5.5. Biomass Yield

In both treatments involving sole soybean and intercropped soybean, it is observed that there is a higher accumulation of biomass [11]. However, there is a significant difference between the two treatments. It is important to note that in mono-cropping systems, where a single crop is cultivated in a field, applying phosphorus fertilizer results in increased biomass production [58]. Phosphorus plays a crucial role in plant growth, root development, and energy transfer processes within the plant. When phosphorus availability is adequate, it enhances photosynthesis, nutrient uptake, and overall plant growth, leading to greater biomass accumulation [59]. This can be seen in **Figure 7**, where a more substantial increase in biomass is observed in R3 maize mono-cropping with fertilizer content, compared to sole maize without fertilizer. The same pattern is evident in the R6 growth stage of soybean, both in sole and intercropped varieties [60]. In sole soybeans, there is a higher biomass accumulation due to reduced competition for nutrients and other resources [61]. In intercropped soybeans, competition for resources such as light, nutrients, and water is significantly higher [57]. The R6 growth stage in soybean is known as the full seed or full pod growth stage, and it is a critical phase in the development of the soybean plant. During this phase, the plant is focused on pod and seed development as it moves toward maturity [54]. At this stage, the plant reaches its maximum height and canopy development and has a well-established root system supporting pod and seed development.

Biomass in the R6 stage of both sole and intercropped soybeans demonstrated an increase in non-fertilized treatments. The R6 stage is a critical reproductive phase where the demand for nutrients is higher to support pod development and seed filling. Despite being non-fertilized, soybean biomass was higher due to its unique ability to fix atmospheric nitrogen through symbiotic relationships with rhizobia bacteria [49]. This nitrogen fixation process continues throughout the plant growth stages and provides a crucial source of nitrogen for pod development and seed filling at the R6 stage [5]. In intercropped soybeans, there was an efficient utilization of nutrients, especially during this critical phase when demand was highest, resulting in maximum biomass production without additional fertilizers [62]. This nutrient remobilization helps sustain high biomass production. The presence of other crops in the intercropped soybean creates a more diverse and dynamic growing environment, which enhances nutrient cycling, improves soil health, and promotes overall plant growth [5]. This contributes to high biomass production in soybeans at the R6 stage.

The outcomes of grain yield for single and intercropped maize in **Figure 6** for fertilized and non-fertilized treatments indicate that in sole maize, the grain yield was low [39]. This may be due to competition among the plants for resources such as sunlight, water, and nutrients [63]. This competition can limit the growth and yield potential of individual plants, leading to decreased overall productivity. In contrast, intercropped maize had relatively higher yields [64]. This may be because maize is a heavy feeder crop that requires significant amounts of nutrients for optimal growth and yield [65]. Non-fertilized treatments in sole maize experienced nutrient deficiencies, which restricted its growth and reduced its yield potential. Intercropped maize, on the other hand, benefited from nutrient cycling and enhanced nutrient availability through interactions with the companion crop, resulting in higher yields [35]. Additionally, cereal-legume intercropping can improve diversification in nutrient uptake by the component crops, increase environmental resource use efficiencies, and result in higher yields per unit area compared to sole cropping [66].

6. Conclusions

It appears from the findings of this study that there is a beneficial interaction between maize and soybean in strip intercropping systems. When choosing crops for such systems, it is essential to consider their complementary traits to avoid potential decreases in grain yield in continuous maize-soybean strip cropping, the use of nitrogen fertilizer is vital. Total grain yield in the intercropping system was higher when nitrogen fertilizer was applied compared to monoculture treatments without fertilizer. Moreover, nitrogen application significantly enhanced nitrogen use efficiency in the system.

Understanding the growth dynamics of maize and soybean in both mono-cropping and intercropping systems, along with the impact of fertilization practices, is crucial for optimizing crop productivity and sustainability in agriculture. For instance, plant height, which peaked at over 200 cm in monoculture maize compared to about 190 cm in intercropped maize at the V10 stage, indicated that competition for resources in intercropped maize can limit growth Phosphorus availability during the V10 stage also plays a crucial role in the growth and performance of maize and soybeans in intercropping systems. Adequate phosphorus levels support healthy root development, nutrient uptake, and overall plant vigor. Conversely, insufficient phosphorus leads to stunted growth, nutrient deficiencies, and reduced productivity in both crops.

Farmers have the opportunity to increase soybean production without compromising maize production and area, potentially enhancing soil fertility and productivity through nitrogen fixation and root exudate release. The combined benefits of nitrogen fixation, nutrient remobilization, efficient nutrient utilization, and intercropping advantages contribute to supporting high soybean yields.

Overall, the combination of nitrogen fixation, nutrient remobilization, efficient nutrient utilization, and potential intercropping benefits all contribute to supporting high soybean biomass production at the critical R6 stage, even in the absence of external fertilizer applications.

Acknowledgements

We extend our gratitude to the data centers that granted us free access to the datasets utilized in our research. Furthermore, we express our appreciation to the Quzhou Experimental Station of the China Agricultural University administration, who graciously allowed and provided the necessary materials for data collection and analysis.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Nurgi, N., Tana, T., Dechassa, N., Tesso, B. and Alemayehu, Y. (2023) Effect of Spatial Arrangement of Faba Bean Variety Intercropping with Maize on Yield and Yield Components of the Crops. *Heliyon*, **9**, e16751. https://doi.org/10.1016/j.heliyon.2023.e16751

[2] Temeche, D., Getachew, E., Hailu, G. and Abebe, A. (2022) Effect of Sorghum-Mung Bean Intercropping on Sorghum-Based Cropping System in the Lowlands of North Shewa, Ethiopia. *Advances in Agriculture*, **2022**, Article ID: 6987871. https://doi.org/10.1155/2022/6987871

[3] Namatsheve, T., Chikowo, R., Corbeels, M., Mouquet-Rivier, C., Icard-Vernière, C. and Cardinael, R. (2021) Maize-Cowpea Intercropping as an Ecological Intensification Option for Low Input Systems in Sub-Humid Zimbabwe: Productivity, Biological N_2-Fixation and Grain Mineral Content. *Field Crops Research*, **263**, Article ID: 108052. https://doi.org/10.1016/j.fcr.2020.108052

[4] Fan, Y., Wang, Z., Liao, D., Raza, M.A., Wang, B., Zhang, J., *et al.* (2020) Uptake and Utilization of Nitrogen, Phosphorus and Potassium as Related to Yield Advantage in Maize-Soybean Intercropping under Different Row Configurations. *Scientific Reports*, **10**, Article No. 9504. https://doi.org/10.1038/s41598-020-66459-y

[5] Kaci, G., Ouaret, W. and Rahmoune, B. (2022) Wheat-Faba Bean Intercrops Improve Plant Nutrition, Yield, and Availability of Nitrogen (N) and Phosphorus (P) in Soil. *Agronomy Research*, **20**, 603-616.

[6] Wu, H., Chen, S., Huang, Z., Huang, T., Tang, X., He, L., *et al.* (2024) Effects of Intercropping and Nitrogen Application on Soil Fertility and Microbial Communities in Peanut Rhizosphere Soil. *Agronomy*, **14**, Article No. 635. https://doi.org/10.3390/agronomy14030635

[7] Kermah, M., Franke, A.C., Adjei-Nsiah, S., Ahiabor, B.D.K., Abaidoo, R.C. and Giller, K.E. (2017) Maize-grain Legume Intercropping for Enhanced Resource Use Efficiency and Crop Productivity in the Guinea Savanna of Northern Ghana. *Field Crops Research*, **213**, 38-50. https://doi.org/10.1016/j.fcr.2017.07.008

[8] Ndayisaba, P.C., Kuyah, S., Midega, C.A.O., Mwangi, P.N. and Khan, Z.R. (2021) Intercropping Desmodium and Maize Improves Nitrogen and Phosphorus Availability and Performance of Maize in Kenya. *Field Crops Research*, **263**, Article ID: 108067. https://doi.org/10.1016/j.fcr.2021.108067

[9] Latati, M., Aouiche, A.R. and Nazih, Y.R. (2018) Intercropping Maize—Common Bean Enhances Microbial Carbon and Nitrogen in Low-Phosphorus Soil under Mediterranean Conditions. *RUDN Journal of Agronomy and Animal Industries*, **13**, 177-184. https://doi.org/10.22363/2312-797x-2018-13-3-177-184

[10] Shao, Z., Wang, X., Gao, Q., Zhang, H., Yu, H., Wang, Y., *et al.* (2020) Root Contact between Maize and Alfalfa Facilitates Nitrogen Transfer and Uptake Using Techniques of Foliar ^{15}N-Labeling. *Agronomy*, **10**, Article No. 360. https://doi.org/10.3390/agronomy10030360

[11] Nasar, J., Zhao, C.J., Khan, R., Gul, H., Gitari, H., Shao, Z., *et al.* (2023) Maize-Soybean Intercropping at Optimal N Fertilization Increases the N Uptake, N Yield and N Use Efficiency of Maize Crop by Regulating the N Assimilatory Enzymes. *Frontiers in Plant Science*, **13**, Article ID: 1077948. https://doi.org/10.3389/fpls.2022.1077948

[12] Latati, M., Aouiche, A., Tellah, S., Laribi, A., Benlahrech, S., Kaci, G., *et al.* (2017) Intercropping Maize and Common Bean Enhances Microbial Carbon and Nitrogen Availability in Low Phosphorus Soil under Mediterranean Conditions. *European Journal of Soil Biology*, **80**, 9-18. https://doi.org/10.1016/j.ejsobi.2017.03.003

[13] Latati, M., Blavet, D., Alkama, N., Laoufi, H., Drevon, J.J., Gérard, F., *et al.* (2014) The Intercropping Cowpea-Maize Improves Soil Phosphorus Availability and Maize Yields in an Alkaline Soil. *Plant and Soil*, **385**, 181-191. https://doi.org/10.1007/s11104-014-2214-6

[14] Latati, M., Pansu, M., Drevon, J. and Mohemed, S. (2013) Advantage of Intercropping Maize (*Zea mays* L.) and Common Bean (*Phaseolus vulgaris* L.) on Yield and Nitrogen Uptake in Northeast Algeria. *International Journal of Research in Applied Sciences*, **1**, 23-29.

[15] Malunga, I., Lelei, J.J. and Makumba, W. (2017) Effect of Mineral Nitrogen and Legume Intercrops on Maize (*Zea mays* L.) Nitrogen Uptake, Nutrient Use Efficiency and Yields in Chitedze and Zomba, Malawi. *Sustainable Agriculture Research*, **7**, 64-79. https://doi.org/10.5539/sar.v7n1p64

[16] Rupp, H., Tauchnitz, N. and Meissner, R. (2024) The Influence of Increasing Mineral Fertilizer Application on Nitrogen Leaching of Arable Land and Grassland—Results of a Long-Term Lysimeter Study. *Frontiers in Soil Science*, **4**, Article ID: 1345073. https://doi.org/10.3389/fsoil.2024.1345073

[17] Xu, Z., Li, C., Zhang, C., Yu, Y., van der Werf, W. and Zhang, F. (2020) Intercropping Maize and Soybean Increases Efficiency of Land and Fertilizer Nitrogen Use; a Meta-Analysis. *Field Crops Research*, **246**, Article ID: 107661. https://doi.org/10.1016/j.fcr.2019.107661

[18] Nurgi, N., Tana, T., Dechassa, N., Alemayehu, Y. and Tesso, B. (2023) Effects of Planting Density and Variety on Productivity of Maize-Faba Bean Intercropping System. *Heliyon*, **9**, e12967. https://doi.org/10.1016/j.heliyon.2023.e12967

[19] Schuster, J., Mittermayer, M., Maidl, F., Nätscher, L. and Hülsbergen, K. (2022)

Spatial Variability of Soil Properties, Nitrogen Balance and Nitrate Leaching Using Digital Methods on Heterogeneous Arable Fields in Southern Germany. *Precision Agriculture*, **24**, 647-676. https://doi.org/10.1007/s11119-022-09967-3

[20] Kamara, A.Y., Tofa, A.I., Ademulegun, T., Solomon, R., Shehu, H., Kamai, N., *et al.* (2017) Maize-Soybean Intercropping for Sustainable Intensification of Cereal-Legume Cropping Systems in Northern Nigeria. *Experimental Agriculture*, **55**, 73-87. https://doi.org/10.1017/s0014479717000564

[21] Nyoki, D. and Ndakidemi, P.A. (2018) Yield Response of Intercropped Soybean and Maize under Rhizobia (*Bradyrhizobium japonicum*) Inoculation and P and K Fertilization. *Communications in Soil Science and Plant Analysis*, **49**, 1168-1185. https://doi.org/10.1080/00103624.2018.1455846

[22] Liu, Y., Bai, M., Shen, F., Wu, Z., Yang, J., Li, N., *et al.* (2024) Enhancing Soybean and Maize Yields through Improved Nitrogen and Soil Water Use Efficiencies: A 40-Year Study on the Impact of Farmyard Manure Amendment in Northeast China. *Plants*, **13**, Article No. 500. https://doi.org/10.3390/plants13040500

[23] Shao, Z., Zheng, C., Postma, J.A., Gao, Q. and Zhang, J. (2024) More N Fertilizer, More Maize, and Less Alfalfa: Maize Benefits from Its Higher N Uptake per Unit Root Length. *Frontiers in Plant Science*, **15**, Article ID: 1338521. https://doi.org/10.3389/fpls.2024.1338521

[24] Mupangwa, W., Nyagumbo, I., Liben, F., Chipindu, L., Craufurd, P. and Mkuhlani, S. (2021) Maize Yields from Rotation and Intercropping Systems with Different Legumes under Conservation Agriculture in Contrasting Agro-Ecologies. *Agriculture, Ecosystems & Environment*, **306**, Article ID: 107170. https://doi.org/10.1016/j.agee.2020.107170

[25] Hidoto, L. and Markos, D. (2021) Effects of Maize/Legume Intercropping on Grain Yield of Component Crops, Land Productivity and Profitability under Conservation Agriculture. *World Journal of Innovative Research*, **11**, 46-51.

[26] Silberg, T.R., Richardson, R.B. and Lopez, M.C. (2020) Maize Farmer Preferences for Intercropping Systems to Reduce Striga in Malawi. *Food Security*, **12**, 269-283. https://doi.org/10.1007/s12571-020-01013-2

[27] Huss, C.P., Holmes, K.D. and Blubaugh, C.K. (2022) Benefits and Risks of Intercropping for Crop Resilience and Pest Management. *Journal of Economic Entomology*, **115**, 1350-1362. https://doi.org/10.1093/jee/toac045

[28] Takele, E., Mekonnen, Z., Tsegaye, D. and Abebe, A. (2017) Effect of Intercropping of Legumes and Rates of Nitrogen Fertilizer on Yield and Yield Components of Maize (*Zea mays* L.) at Arba Minch. *American Journal of Plant Sciences*, **8**, 2159-2179. https://doi.org/10.4236/ajps.2017.89145

[29] Pelech, E.A., Evers, J.B., Pederson, T.L., Drag, D.W., Fu, P. and Bernacchi, C.J. (2022) Leaf, Plant, to Canopy: A Mechanistic Study on Aboveground Plasticity and Plant Density within a Maize-Soybean Intercrop System for the Midwest, USA. *Plant, Cell & Environment*, **46**, 405-421. https://doi.org/10.1111/pce.14487

[30] van Es, H. (2023) Cold Climate Factors in Nitrogen Management for Maize. *Agriculture*, **14**, Article No. 85. https://doi.org/10.3390/agriculture14010085

[31] Ariel, C.E. (2013) Effects of Two Plant Arrangements in Corn (*Zea mays* L.) and Soybean (*Glycine max* L. Merrill) Intercropping on Soil Nitrogen and Phosphorus Status and Growth of Component Crops at an Argentinean Argiudoll. *American Journal of Agriculture and Forestry*, **1**, 22-31. https://doi.org/10.11648/j.ajaf.20130102.11

[32] Li, Y., He, N., Hou, J., Xu, L., Liu, C., Zhang, J., *et al.* (2018) Factors Influencing

Leaf Chlorophyll Content in Natural Forests at the Biome Scale. *Frontiers in Ecology and Evolution*, **6**, Article No. 64. https://doi.org/10.3389/fevo.2018.00064

[33] Olubode, O.O. (2019) Influence of Seasonal Variability of Precipitation and Temperature on Performances of Pawpaw Varieties Intercropped with Cucumber. *Scientia Horticulturae*, **243**, 622-644. https://doi.org/10.1016/j.scienta.2018.06.007

[34] Nwokoro, C.C., Kreye, C., Necpalova, M., Adeyemi, O., Barthel, M., Pypers, P., *et al.* (2022) Cassava-Maize Intercropping Systems in Southern Nigeria: Radiation Use Efficiency, Soil Moisture Dynamics, and Yields of Component Crops. *Field Crops Research*, **283**, Article ID: 108550. https://doi.org/10.1016/j.fcr.2022.108550

[35] Raza, M.A., Yasin, H.S., Gul, H., Qin, R., Mohi Ud Din, A., Khalid, M.H.B., *et al.* (2022) Maize/Soybean Strip Intercropping Produces Higher Crop Yields and Saves Water under Semi-Arid Conditions. *Frontiers in Plant Science*, **13**, Article ID: 1006720. https://doi.org/10.3389/fpls.2022.1006720

[36] Morugán-Coronado, A., Linares, C., Gómez-López, M.D., Faz, Á. and Zornoza, R. (2020) The Impact of Intercropping, Tillage and Fertilizer Type on Soil and Crop Yield in Fruit Orchards under Mediterranean Conditions: A Meta-Analysis of Field Studies. *Agricultural Systems*, **178**, Article ID: 102736. https://doi.org/10.1016/j.agsy.2019.102736

[37] Silva, J. and Uchida, R. (2000) Essential Nutrients for Plant Growth: Nutrient Functions and Deficiency Symptoms. Plant Nutrient Management in Hawaii's Soils, Approaches for Tropical and Subtropical Agriculture, College of Tropical Agriculture and Human Resources, University of Hawaii at Manoa, Honolulu, 31-55.

[38] Tolera, A., Dagne, W. and Tolessa, D. (2019) Nitrogen Use Efficiency and Yield of Maize Varieties as Affected by Nitrogen Rate in Mid Altitude Areas of Western Ethiopia. 1-30.

[39] Kutamahufa, M., Matare, L., Soropa, G., Mashavakure, N., Svotwa, E. and Mashingaidze, A.B. (2021) Forage Legumes Exhibit a Differential Potential to Compete against Maize and Weeds and to Restore Soil Fertility in a Maize-Forage Legume Intercrop. *Acta Agriculturae Scandinavica, Section B—Soil & Plant Science*, **72**, 127-141. https://doi.org/10.1080/09064710.2021.1998593

[40] Mucheru-Muna, M., Pypers, P., Mugendi, D., Kung'u, J., Mugwe, J., Merckx, R., *et al.* (2010) A Staggered Maize-legume Intercrop Arrangement Robustly Increases Crop Yields and Economic Returns in the Highlands of Central Kenya. *Field Crops Research*, **115**, 132-139. https://doi.org/10.1016/j.fcr.2009.10.013

[41] Adhikari, K., Bhandari, S., Aryal, K., Mahato, M. and Shrestha, J. (2021) Effect of Different Levels of Nitrogen on Growth and Yield of Hybrid Maize (*Zea mays* L.) Varieties. *Journal of Agriculture and Natural Resources*, **4**, 48-62. https://doi.org/10.3126/janr.v4i2.33656

[42] Ronner, E., Thuijsman, E., Ebanyat, P., Descheemaeker, K. and Giller, K.E. (2021) Intercropping of Climbing Bean (*Phaseolus vulgaris*, L.) and East African Highland Banana (Musa Spp.) in the Ugandan Highlands. *Experimental Agriculture*, **57**, 1-14. https://doi.org/10.1017/s0014479720000411

[43] Karanja, S.M., Kibe, A.M., Karogo, P.N. and Mwangi, M. (2014) Effects of Intercrop Population Density and Row Orientation on Growth and Yields of Sorghum—Cowpea Cropping Systems in Semi Arid Rongai, Kenya. *Journal of Agricultural Science*, **6**, 34-43. https://doi.org/10.5539/jas.v6n5p34

[44] Couvreur, T.L.P., Dauby, G., Blach‐Overgaard, A., Deblauwe, V., Dessein, S., Droissart, V., *et al.* (2020) Tectonics, Climate and the Diversification of the Tropical African Terrestrial Flora and Fauna. *Biological Reviews*, **96**, 16-51.

https://doi.org/10.1111/brv.12644

[45] Tsubo, M. and Walker, S. (2004) Shade Effects on *Phaseolus vulgaris* L. Intercropped with *Zea mays* L. under Well-Watered Conditions. *Journal of Agronomy and Crop Science*, **190**, 168-176. https://doi.org/10.1111/j.1439-037x.2004.00089.x

[46] Huang, C., Liu, Q., Li, X. and Zhang, C. (2019) Effect of Intercropping on Maize Grain Yield and Yield Components. *Journal of Integrative Agriculture*, **18**, 1690-1700. https://doi.org/10.1016/s2095-3119(19)62648-1

[47] Kermah, M., Franke, A.C., Adjei-Nsiah, S., Ahiabor, B.D.K., Abaidoo, R.C. and Giller, K.E. (2017) Maize-Grain Legume Intercropping for Enhanced Resource Use Efficiency and Crop Productivity in the Guinea Savanna of Northern Ghana. *Field Crops Research*, **213**, 38-50. https://doi.org/10.1016/j.fcr.2017.07.008

[48] Salomons, M., *et al.* (2018) Intercropping in Zimbabwe Conservation Agriculture Systems Using a Farmer-Participatory Research Approach. *African Journal of Agricultural Research*, **13**, 1531-1539. https://doi.org/10.5897/ajar2018.13238

[49] Gitari, H.I., Karanja, N.N., Gachene, C.K.K., Kamau, S., Sharma, K. and Schulte-Geldermann, E. (2018) Nitrogen and Phosphorous Uptake by Potato (*Solanum tuberosum* L.) and Their Use Efficiency under Potato-Legume Intercropping Systems. *Field Crops Research*, **222**, 78-84. https://doi.org/10.1016/j.fcr.2018.03.019

[50] Nyawade, S., Karanja, N., Gachene, C., Parker, M. and Schulte-Geldermann, E. (2018) Susceptibility of Soil Organic Matter Fractions to Soil Erosion under Potato-to-Legume Intercropping Systems in Central Kenya. *Journal of Soil and Water Conservation*, **73**, 567-576. https://doi.org/10.2489/jswc.73.5.567

[51] Chen, P., Du, Q., Liu, X., Zhou, L., Hussain, S., Lei, L., *et al.* (2017) Effects of Reduced Nitrogen Inputs on Crop Yield and Nitrogen Use Efficiency in a Long-Term Maize-Soybean Relay Strip Intercropping System. *PLOS ONE*, **12**, e0184503. https://doi.org/10.1371/journal.pone.0184503

[52] Mndzebele, B., Ncube, B., Fessehazion, M., Mabhaudhi, T., Amoo, S., du Plooy, C., *et al.* (2020) Effects of Cowpea-Amaranth Intercropping and Fertiliser Application on Soil Phosphatase Activities, Available Soil Phosphorus, and Crop Growth Response. *Agronomy*, **10**, Article No. 79. https://doi.org/10.3390/agronomy10010079

[53] Raza, M.A., Bin Khalid, M.H., Zhang, X., Feng, L.Y., Khan, I., Hassan, M.J., *et al.* (2019) Effect of Planting Patterns on Yield, Nutrient Accumulation and Distribution in Maize and Soybean under Relay Intercropping Systems. *Scientific Reports*, **9**, Article No. 4947. https://doi.org/10.1038/s41598-019-41364-1

[54] Khalid, M.H.B., Cui, L., Abbas, G., Raza, M.A., Anwar, A., Ahmed, Z., *et al.* (2023) Effect of Row Spacing under Maize-Soybean Relay Intercropping System on Yield, Competition, and Economic Returns. *Turkish Journal of Agriculture and Forestry*, **47**, 390-401. https://doi.org/10.55730/1300-011x.3095

[55] Daryanto, S., Fu, B., Zhao, W., Wang, S., Jacinthe, P. and Wang, L. (2020) Ecosystem Service Provision of Grain Legume and Cereal Intercropping in Africa. *Agricultural Systems*, **178**, Article ID: 102761. https://doi.org/10.1016/j.agsy.2019.102761

[56] Nassary, E.K., Baijukya, F. and Ndakidemi, P.A. (2020) Productivity of Intercropping with Maize and Common Bean over Five Cropping Seasons on Smallholder Farms of Tanzania. *European Journal of Agronomy*, **113**, Article ID: 125964. https://doi.org/10.1016/j.eja.2019.125964

[57] Li, C., Hoffland, E., Kuyper, T.W., Yu, Y., Zhang, C., Li, H., *et al.* (2020) Syndromes of Production in Intercropping Impact Yield Gains. *Nature Plants*, **6**, 653-660. https://doi.org/10.1038/s41477-020-0680-9

[58] Li, C., Kuyper, T.W., van der Werf, W., Zhang, J., Li, H., Zhang, F., *et al.* (2018) Testing for Complementarity in Phosphorus Resource Use by Mixtures of Crop Species. *Plant and Soil*, **439**, 163-177. https://doi.org/10.1007/s11104-018-3732-4

[59] Fu, Z., Zhou, L., Chen, P., Du, Q., Pang, T., Song, C., *et al.* (2019) Effects of Maize-Soybean Relay Intercropping on Crop Nutrient Uptake and Soil Bacterial Community. *Journal of Integrative Agriculture*, **18**, 2006-2018. https://doi.org/10.1016/s2095-3119(18)62114-8

[60] Ravensbergen, P. (2018) Trade-Off Analysis of Integrating Legumes in East-African Maize Cropping Systems.

[61] Sogoba, B., Traoré, B., Safia, A., Samaké, O.B., Dembélé, G., Diallo, S., *et al.* (2020) On-farm Evaluation on Yield and Economic Performance of Cereal-Cowpea Intercropping to Support the Smallholder Farming System in the Soudano-Sahelian Zone of Mali. *Agriculture*, **10**, Article No. 214. https://doi.org/10.3390/agriculture10060214

[62] Kolawole, G.O. (2012) Effect of Phosphorus Fertilizer Application on the Performance of Maize/Soybean Intercrop in the Southern Guinea Savanna of Nigeria. *Archives of Agronomy and Soil Science*, **58**, 189-198. https://doi.org/10.1080/03650340.2010.512723

[63] Nyoki, D. (2014) Effects of *Bradyrhizobium japonicum* and Phosphorus Supplementation on the Productivity of Legumes. *International Journal of Plant & Soil Science*, **3**, 894-910. https://doi.org/10.9734/ijpss/2014/8412

[64] Mudare, S., Kanomanyanga, J., Jiao, X., Mabasa, S., Lamichhane, J.R., Jing, J., *et al.* (2022) Yield and Fertilizer Benefits of Maize/Grain Legume Intercropping in China and Africa: A Meta-Analysis. *Agronomy for Sustainable Development*, **42**, Article No. 81. https://doi.org/10.1007/s13593-022-00816-1

[65] Jiao, N., Wang, J., Ma, C., Zhang, C., Guo, D., Zhang, F., *et al.* (2021) The Importance of Aboveground and Belowground Interspecific Interactions in Determining Crop Growth and Advantages of Peanut/Maize Intercropping. *The Crop Journal*, **9**, 1460-1469. https://doi.org/10.1016/j.cj.2020.12.004

[66] Liben, F.M., Tadesse, B., Tola, Y.T., Wortmann, C.S., Kim, H.K. and Mupangwa, W. (2018) Conservation Agriculture Effects on Crop Productivity and Soil Properties in Ethiopia. *Agronomy Journal*, **110**, 758-767. https://doi.org/10.2134/agronj2017.07.0384