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Organic nutrient management improves crop growth kinetics and resource use efficiency in wheat chickpea intercropping systems

Guntimadugu Sanhthosh Kumar Raju
Lovely Professional University
Sandeep Menon
Lovely Professional University
Arun Kumar
arun.kumar@jaipur.manipal.edu

Manipal University Jaipur
Jayanthi J
Manipal University Jaipur
Burra Shyamsunder
Guru Nanak University
Thulisekari Prasanna
SR University
Ishwar Singh
Maharishi Markandeshwar University, Mullana
Siddharth .
Maharishi Markandeshwar University, Mullana

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Abstract

A mechanistic understanding of the interactions between biologically driven nutrient management and crop diversification in regulating plant growth dynamics is required for the sustainable intensification of cereal-based systems. The present study investigated the combined effect of integrated organic amendments and biofertilizers on the kinetics of crop growth in wheat–chickpea intercropping systems under different spatial arrangements. A field experiment was conducted in a split-plot design with three cropping systems (sole wheat, 2:2, and 3:1 wheat–chickpea intercropping) and four organic nutrient treatments (farmyard manure, vermicompost, poultry manure, and biofertilizers (Azotobacter and phosphate-solubilizing bacteria). Main growth stages were used to measure growth kinetics (crop growth rate (CGR), relative growth rate (RGR), and absolute growth rate (AGR)) and biomass accumulation. Growth kinetics were significantly improved with integrated organic nutrient management compared with the control. The highest CGR, RGR, and AGR were obtained with the integrated application of farmyard manure (5 t ha-1) and poultry manure (2 t ha-1) along with biofertilizer. Intercropping systems consistently outperformed sole cropping, with the 2:2 configuration promoting higher early growth, while the 3:1 system sustained greater growth later in the season, reflecting temporal shifts in resource complementarity. These responses were linked to improved nutrient synchronization, increased microbial activity, and more efficient partitioning of resources between component crops. Importantly, this study demonstrates that growth kinetics are strong integrative indicators that link soil-mediated nutrient dynamics to plants' physiological responses. Growth analysis and multivariate methods were integrated to construct a process-based framework for the joint regulation of crop performance by organic nutrient management and intercropping. These results provide a mechanistic basis for optimizing cereal–legume systems and developing sustainable intensification strategies.

1. Introduction

Agricultural operations all over the world are encountering difficulties in producing increased yields of crops, and at the same time keeping their soil productive without being environmentally stressed, and amidst scarce resources. The application of synthetic fertilizers has significantly contributed to raising agricultural yields, but such a practice has also resulted in loss of organic carbon in the soil, soil microbial disturbances, and inefficient nutrient uptake, particularly in cereal and legume production (Lal, 2015; Lal, 2020; Manqiang et al., 2009). The addition of organic inputs such as farm yard manure, vermicompost, and poultry manure is a potential sustainable approach to restoring soil fertility and achieving optimum agricultural production (Goyal et al., 1999; Liu et al., 2009). This is because organic inputs enhance soil quality by improving soil physical properties, increasing the soil's capacity to retain moisture, and promoting microbial population, hence the mineralization process (Nardi et al., 2002; Geisseler & Scow, 2014; Shaji et al., 2021; Diacono & Montemurro, 2010). Moreover, because of their high carbon content, they serve as sources that help in enhancing microbial biomass in the rhizosphere and drive nutrient cycling through enzymatic action (Elfstrand et al., 2007; Sánchez-Monedero et al., 2004). As compared to mineral fertilizer, organic amendment offers a biologically controlled source of nutrients. The use of these amendments alongside bio-fertilizers, such as Azotobacter and PSB, helps in making nitrogen and phosphorus available for use through biological nitrogen fixation and phosphorus solubilization (Bhattacharyya et al., 2012; Vessey, 2003; Adesemoye et al., 2009; Rudresh et al., 2005).

Intercropping cereal crops with leguminous plants is one such complementary strategy in agroecology aimed at maximizing resource use efficiency and resilience (Li et al., 2014). For instance, legumes have the capability to biologically fix nitrogen and release substances from their roots, which stimulates the activities of microorganisms, thereby ensuring better nutrient availability for the companion cereal crops (Fujita et al., 1992; Bedoussac et al., 2015; Louarn et al., 2021). Additionally, intercropping ensures better efficiency in the utilization of land, weed management, and stability of the agricultural production system in limited-resource environments (Willey et al., 1979; Banik et al., 2006; Glaze-Corcoran et al., 2020; Latati et al., 2019). Higher growth and productivity under the intercropping condition in wheat-chickpea crop systems can be attributed to complementary resource use due to differences in rooting depth, canopy structure, and nutrient requirements.

While significant strides have been made, most research in this area has concentrated on the impacts of organic nutrient management and intercropping on yields without considering the physiological basis behind these plant responses. Crop yield is intrinsically associated with physiological growth processes and can therefore be better evaluated using growth measures like crop growth rate (CGR), relative growth rate (RGR), and absolute growth rate (AGR). These growth measures incorporate important physiological aspects such as biomass development, photosynthesis, and nutrient absorption, thereby giving a better insight into plant response mechanisms to various treatments (Blackman, 1919; Watson, 1952; Hunt, 1990). In contrast, there are existing findings that demonstrate that organic fertilizers and intercropping affect growth rates (Namvar et al., 2011; Seth and Kumar, 2019), it is still unclear how these two variables affect each other’s growth dynamics.

It is important to note that the impacts of organic amendments on plant development will always be dynamic due to the process of nutrient mineralization over time and their role within the soil microbial population. In the case of an intercropping system, these impacts will be further shaped by the arrangement and interactions among species within the planting scheme, thereby affecting factors such as light interception, root proliferation, and nutrient distribution (Singh & Sarawgi, 1995; Lithourgidis et al., 2011). Despite this, however, the relationship between the two remains unclear. It is therefore essential to develop a process-based model that will help to establish the connection between the

processes occurring within the soil and the growth of plants through the process of organic nutrient management in conjunction with intercropping. This can be achieved through the use of plant growth kinetics (Poorter & Garnier, 2007) whereby temporal changes in biomass production are correlated with physiological and biochemical processes.

In summary, the objective of this study is to investigate the combined effects of organic nutrient supply and intercropping pattern on crop growth kinetics using an integrated approach involving growth kinetics and multivariate analysis. The study takes a step forward from yield-based studies by providing a mechanistic understanding of cereal-legume cropping systems (Tuck et al., 2014).

Conceptual framework: Linking organic amendments to crop growth kinetics in cereal–legume intercropping systems

The operations of the cereal-legume intercropping system under the organic nutrient management regime depend on the soil-microbe-plant interaction process, which controls the availability of nutrients and their uptake by the crops. Whereas chemical fertilizers have immediate availability of nutrients, there is a dependency on organic matter in providing nutrients through microbial activity that causes time-dependent nutrient release, thus coordinating nutrient availability with plant nutrient uptake. This timing is essential in influencing the growth rate of biological nutrient management systems. In the soil system, organic input serves two purposes: providing nutrients and energy to the system for the growth of microorganisms, enzyme activities, and the transformation of nutrients. Such conditions facilitate the process of nutrient mineralization and mobilization of nutrients such as nitrogen and phosphorus. Additionally, the presence of bio-fertilizers enhances the process of nitrogen fixation and phosphorus mobilization within the system. The processes influence the physiological functioning of the plant such as photosynthesis, root growth, and nutrient uptake. This translates to increased biomass production and proper distribution of the product obtained. The plant's physiological responses are very well captured using growth kinetics, which comprise crop growth rate (CGR), relative growth rate (RGR), and absolute growth rate (AGR). In organically managed agricultural systems, nutrient release is slow and controlled by microbes; hence, growth kinetics are an excellent indicator of nutrient utilization efficiency in plants (Six et al., 2006).

In agroecological systems such as intercrops, physiological responses in plants are also dependent on the physiological interactions that occur between the crops. For instance, leguminous plants provide nitrogen to the environment and, through root secretions (Hauggaard-Nielsen & Jensen 2005) facilitate rhizospheric microbial activity, thereby making nutrients available to the cereal crops associated with the legumes.

Spatial geometry plays the role of an important regulating factor in this regard by controlling the balance between complementarity and competition. The effect of different row ratios will influence factors like light interception, overlapping roots, and nutrient availability, hence affecting microbial activities and plant physiology. Effective geometric spacing optimizes resource allocation, while ineffective spacing might increase competition among species, thus reducing growth.

From the above discussion, it is evident that organic fertilizers affect crop growth via microbial activity-driven nutrients synchronization, and geometric intercropping affects this through resource partitioning and interspecific competition. The kinetics of growth act as an integration point connecting soil microbiology with plant physiology to optimize resource use efficiency and crop production. This biogeochemical process-oriented model provides a basis for optimization of crop growth in sustainable agriculture.

Objectives

The present study aims to develop a process-based understanding of how organic nutrient management interacts with intercropping design to regulate crop growth dynamics in wheat–chickpea systems.

The specific objectives were to:

1. quantify the effects of integrated organic amendments and biofertilizers on crop growth kinetics (CGR, RGR, AGR);
2. evaluate the influence of intercropping geometry on temporal growth dynamics and biomass accumulation of component crops; and
3. elucidate the mechanistic link between soil-mediated nutrient availability and plant physiological responses in cereal–legume intercropping systems.

Hypotheses

H1: Integrated application of organic amendments and biofertilizers enhances crop growth kinetics by improving microbially mediated nutrient availability and synchronization with crop demand.

H2: Intercropping systems exhibit higher growth efficiency than sole cropping due to complementary resource use and facilitative interactions between cereal and legume components.

H3: Intercropping geometry regulates growth dynamics by influencing light interception, root distribution, and interspecific competition, thereby affecting crop growth kinetics.

H4: Growth kinetics (CGR, RGR, AGR) serve as robust integrative indicators linking soil nutrient dynamics with plant physiological performance in organically managed intercropping systems.

2. Materials and Methods

2.1 Experimental site and soil characteristics

The field experiment was conducted in the two consecutive rabi crop periods in 2020 and 2021 on the research farm of Lovely Professional University, Phagwara, Punjab, India (31°15'N; 75°42'E; elevation 250 m above mean sea level). Data obtained from the two years were combined for statistical analysis. The locality has a semi-arid subtropical climate with cool winters and moderate precipitation during the growing period.

The soil of the experimental site was sandy loam in texture and nearly neutral to slightly alkaline in reaction (pH 6.8–7.3). Organic carbon and nitrogen contents were relatively low in the soil with respect to the values of phosphorus and potassium, whereas bulk density was moderate (organic carbon—0.45%; nitrogen—213 kg ha^{-1}, phosphorus—35 kg ha^{-1}, potassium—278.8 kg ha^{-1}; bulk density—1.08 g cm^{-3}). Soil initial characteristics were measured before sowing.

2.2 Experimental design and treatments

The experimental design involved a split-plot design replicated thrice. Main plots contained treatments associated with cropping systems, while subplot treatments included those associated with organic nutrient management. Split-plot design is one of the most common designs employed when assessing the interaction effects of cropping systems and nutrient management on crops grown under field conditions (Banik et al., 2006; Lithourgidis et al., 2006).

The main-plot treatments consisted of:

- Sole wheat
- Wheat–chickpea intercropping in a 2:2 row ratio
- Wheat–chickpea intercropping in a 3:1 row ratio

The subplot treatments comprised four organic nutrient management strategies:

1. Control (no organic inputs)
2. Farmyard manure (FYM 10 t ha^{-1}) + vermicompost (6 t ha^{-1}) + Azotobacter + PSB
3. FYM (5 t ha^{-1}) + poultry manure (2 t ha^{-1}) + Azotobacter + PSB
4. Vermicompost (3 t ha^{-1}) + poultry manure (2 t ha^{-1}) + Azotobacter + PSB

2.3 Crop establishment and management

Certified seeds of wheat and chickpea were procured from the Punjab Agricultural University, Ludhiana, Punjab, India. The experimental field was located at the research farm of Lovely Professional University (31°15'N, 75°42'E). The plant materials used in the study were cultivated crop varieties commonly grown under regional agronomic conditions. The crops were sown based on their respective treatment geometries. Wheat was sown at a rate of 100 kg/ha with an intra-row spacing of 10 cm, while chickpea was planted at 80 kg/ha with a row spacing of 20 cm. Intercropping experiments were laid out in accordance with a replacement series design that helps maintain an equal plant population and only varies the proportion of species (Banik et al., 2006). The row placement was adjusted depending on the respective ratios (2:2 and 3:1).

Bio-fertilizers and organic manures were added and mixed into the soil before sowing. Microbial inoculants (Azotobacter and phosphatesolubilizing bacteria) were added along with organic manures to promote colonization in the rhizosphere. Studies reveal the efficacy of these microorganisms in promoting fixation of nitrogen and liberation of phosphates in the soil (Vessey, 2003; Rudresh et al., 2005). All experimental plots were maintained under appropriate agronomic practices, including irrigation, weeding, and protection from pests.

2.4 Measurement of growth parameters

Growth data was collected on days 30, 60, and 90 after planting (DAP) and during harvest. The following growth attributes for wheat were determined: plant height (cm), number of tillers per plant, and dry matter accumulation (g plant⁻¹). For the chickpea crop, the following attributes were considered: plant height (cm), number of branches per plant, and dry biomass (g plant⁻¹). The measurements were conducted on randomly selected samples from each field plot. The plant samples were dried at temperatures of 65–70°C to constant weight.

2.5 Growth kinetics analysis

Crop growth kinetics were quantified using standard growth indices based on sequential biomass measurements, following established growth analysis procedures (Blackman, 1919; Watson, 1952; Hunt, 1990; Namvar et al., 2011).

$$\varvec{C}\varvec{G}\varvec{R} = \frac{\varvec{W}_2 - \varvec{W}_1}{\varvec{t}_2 - \varvec{t}_1}$$

$$\varvec{R}\varvec{G}\varvec{R} = \frac{\mathbf{ln}\varvec{W}_2 - \mathbf{ln}\varvec{W}_1}{\varvec{t}_2 - \varvec{t}_1}$$

$$\varvec{A}\varvec{G}\varvec{R} = \frac{\varvec{H}_2 - \varvec{H}_1}{\varvec{t}_2 - \varvec{t}_1}$$

where $W_1$and W_2represent plant dry weight at times $t_1$and t_2, respectively, and $H_1$and H_2denote plant height at corresponding sampling intervals. CGR was expressed as dry matter accumulation per unit ground area per unit time, RGR as biomass increase relative to existing biomass, and AGR as the rate of increase in plant height over time.

2.6 Statistical and multivariate analysis

Data was analyzed by one-way analysis of variance (ANOVA) for a split-plot design in order to determine the effects of crop type, organic nutrient application, and their interactions on crop yield and growth kinetics. Analyses were done with the help of OPSTAT software, and comparison of treatment means was carried out based on the LSD test at 5% probability level ($p \leq 0.05$). Multivariate analysis was also done to identify correlations among growth characteristics. Principal component analysis was done using Python (version 3.10.0) through the scikit-learn library after standardization of variables. Growth parameters were represented through PC1 and PC2. Pearson correlation analysis was conducted to see the correlation among growth kinetics (CGR, RGR, AGR). The correlation matrix was visualized as a heatmap using the seaborn library.

3. Result

3.1 Growth kinetics of wheat

The growth parameters (CGR, RGR, and AGR) of wheat crops were found to be significantly affected by the cropping system and use of organic nutrients throughout different growth stages (Table 1). Intercrop systems improved growth rates as compared to sole wheat crops, depending on the temporal response. The 2:2 wheat-chickpea intercrop system showed increased CGR values (0.156 and 0.795 g m⁻² day⁻¹) in early and mid-growth stages (0–30 days after sowing [DAS] and 30–60 DAS, respectively), which were 11–24% greater than sole wheat growth. In the late growth stage (60–90 DAS), the 3:1 intercrop system revealed maximum CGR (4.944 g m⁻² day⁻¹) for enhanced biomass production in cereal-rich intercrop systems. Similarly, RGR was higher in the intercrop systems compared to sole wheat crops during 30–60 DAS in the 2:2 system. However, in late stages (60–90 DAS), the RGR values remained relatively high in the 3:1 intercrop system. AGR was also increased in intercrop systems, especially the 3:1 intercrop system during 60–90 DAS, showing maximum growth (1.012 cm day⁻¹), reflecting enhanced vertical growth at later stages.

Organic nutrient management had a significant impact on growth kinetics. The simultaneous application of FYM at 5 t ha⁻¹ and poultry manure at 2 t ha⁻¹, along with biofertilizers, exhibited maximum CGR values at all growth phases, showing increments of 50%–170% relative to the control. An analogous pattern was noted for RGR and AGR, demonstrating that organic nutrient management had increased growth kinetics relative to control.

3.2 Growth kinetics of chickpea

The growth kinetic parameters of the chickpea plants were strongly influenced by the two factors (intercropping geometry and organic nutrient supply) (Table 4). The 2:2 cropping geometry had better CGR values in the early (0–30 DAS) and mid stages (30–60 DAS) of growth, signifying enhanced growth in balanced crop geometry. On the other hand, differences among cropping geometries started narrowing down towards the late stages (60–90 DAS); however, even then, the 2:2 cropping geometry exhibited a better CGR value. Similarly, RGR was observed to be better in the 2:2 cropping geometry in the early stages; however, the difference between cropping geometries became insignificant in the later stages.

Interestingly, AGR of 3:1 cropping geometry remained comparatively higher in the 60–90 DAS stage (0.886 cm day^{-1}), signifying better growth in terms of height increase in lesser interspecific competition.

Significantly better growth kinetics of chickpea plants were achieved through the application of organic nutrients. Application of VC (3 t ha^{-1}) + PM (2 t ha^{-1}) + biofertilizers led to the highest CGR at the late stage, increasing CGR by almost 80%. Also, the FYM + PM + biofertilizers combination resulted in consistently high RGR and AGR values, indicating improved growth efficiency and structural development across stages.

3.3 Biomass accumulation and growth traits of wheat

Growth characteristics, such as height, tillers, and dry matter accumulation of the wheat crop, showed significant variation due to the effect of cropping pattern and nutrient management (Table 3). Inter-cropped patterns of cultivation led to higher biomass and tillers than monoculture wheat, especially during late developmental stages. The highest number of tillers was observed with the 2:2 cropping pattern at 90 DAS, while 3:1 showed higher dry matter accumulation, suggesting better biomass distribution with cereal-dominant intercropping patterns. Nutrient management through organic sources significantly increased the values for all the growth characteristics. The combination of FYM + PM + biofertilizer resulted in the highest plant height, tiller number, and dry weight with an increase of 9%, 44%, and 138%, respectively.

3.4 Biomass accumulation and growth traits of chickpea

Several factors related to the growth of chickpeas, such as plant height, branching, and accumulation of dry matter, differed significantly among cropping systems and organic nutrient management (Table 2). Intercropping system 2:2 showed higher accumulation of dry matter at 90 DAS, while plant height was slightly higher for the 3:1 intercropping system. There was very little difference observed in the branching trait among intercropping systems.

Growth attributes of chickpeas were greatly improved due to organic nutrient management. Application of FYM + PM+biofertilizer produced maximum plant height and branching, whereas maximum dry matter accumulation was obtained from the VC + PM combination. Organic nutrient management gave 55–65% higher biomass and 40–50% higher branching compared to control plants.

3.5 Interaction effects of cropping system and nutrient management

Substantial interaction effects were recorded between cropping systems and organic nutrient management with respect to most growth indices ($p < 0.05$). The intercropping system with organic nutrient management yielded the greatest response for plant growth. The use of FYM, PM, and biofertilizer in the intercropping system (2:2 and 3:1) showed an outstanding performance in CGR, RGR, AGR, and biomass production compared to the sole cropping system under controlled conditions.

3.6 Principal component analysis and correlation heatmap

The principal component analysis (PCA) results exhibited separation of treatments for the growth performance of all parameters taken as a whole (Fig. 1A-B). The contribution of the first principal component (PC1) accounted for 93.1% of the total variability, demonstrating that most of the growth parameters had been controlled by an overarching performance axis comprising growth kinetics and biomass production. While the second principal component (PC2) had a contribution rate of 6%, it accounted for small variations amongst the organic treatments.

The treatment group was distinctly separated on PC1 into two classes, namely control and integrated organic treatments, which is indicative of improved growth performance in the case of integrated organic nutrients. The integrated treatments had formed a distinct cluster among themselves, showing enhanced growth in all organic treatments. Within these, a distinctive cluster of FYM + PM + biofertilizers had been formed.

The correlation study revealed a strong positive relationship between growth kinetics and biomass parameters (Fig. 1C). The growth rate constant (CGR) revealed a very close association with the biomass of wheat ($r \approx 1.00$), along with a positive correlation with the biomass of chickpea and branching. Likewise, relative growth rate (RGR) and absolute growth rate (AGR) also showed positive associations with biomass production. In sum, it can be said that multivariate analysis reveals a high degree of association between growth kinetics and biomass attributes.

4. Discussion

4.1 Organic amendments regulate growth through nutrient synchronization

The better growth kinetics seen under the integrated use of organic nutrient management is attributed to better coordination between nutrient availability and demand. Whereas mineral fertilizers release nutrients instantaneously into the soil system, organic fertilizers are gradually broken down by soil microorganisms leading to a continuous nutrient supply during the entire period of plant development (Edmeades et al.,

2003; Vanlauwe et al., 2015; Lal, 2020; Manqiang et al., 2009). Coordination is very important for achieving high levels of CGR and RGR in both the vegetative and reproductive phases, as seen in this study. The higher effectiveness of mixed application of organic materials (FYM + PM + biofertilizers) is a demonstration of a synergistic effect between the two mechanisms involved. Organics serve as carbon sources to microorganisms, stimulating their growth and metabolic activities, which help in mineralizing and transforming nutrients (Hayat et al., 2010: Elfstrand et al., 2007; Sánchez-Monedero et al., 2004). Also, the addition of plant growth-promoting rhizobacteria (PGPR) promotes nitrogen fixing and phosphate solubilizing activities in the rhizosphere (Philippot et al., 2013; Vessey, 2003; Adesemoye et al., 2009; Rudresh et al., 2005). The marked increase in CGR and AGR, especially in the later growth stages, suggests an effective matching of nutrient availability from organic sources to crop requirements. Such results have been observed in organic agricultural systems over time, wherein better microbial activities and nutrient cycling contribute to increased efficiency of plant growth and biomass production (Lori et al., 2017; Diacono and Montemurro, 2010). This clearly emphasizes the role of organic nutrients in achieving consistent growth and biological control of growth processes.

4.2 Intercropping-mediated complementarity enhances growth efficiency

The better growth dynamics of wheat and chickpea within intercropping systems demonstrate the significance of complementary utilization of resources and synergism among the individual components of the crop combination. Legume species deliver fixed forms of nitrogen by means of nitrogen fixation, thus increasing the levels of nitrogen available to cereal crops and improving their yield (Zhang et al., 2003; Fujita et al., 1992; Bedoussac et al., 2015; Louarn et al., 2021). Apart from delivering nitrogen molecules to the roots, root exudates in legume plants contribute to the multiplication of microorganisms, making the process of nutrient cycling faster and increasing soil fertility. Greater CGR and RGR values observed in crop intercropping may indicate increased efficiency of resources utilization. This might have been caused by differences in root and canopy architecture, resulting in the emergence of spatiotemporal niches (Glaze-Corcoran et al., 2020; Lithourgidis et al., 2006). The difference in performance among the different systems is attributable to the balance between complementarity and competition. The 2:2 system facilitated more growth at an earlier stage because of the equal proportion of the crops and better light capture, while the 3:1 system facilitated more growth at a later stage due to the dominance of cereals. This is in line with past research showing how cereal-legume intercropping improves growth dynamics by promoting complementarity and minimizing interspecific competition (Latati et al., 2019; Brooker et al., 2015).

4.3 Influence of intercropping geometry on growth dynamics

The geometry of intercropping was an important determinant of the regulation of growth kinetics through the effects on complementarity and competition. Different row ratios had an effect on resource distribution spatially, such as light interception, root interaction, and nutrient uptake, thereby having an effect on growth kinetics at different stages. High early growth kinetics in the 2:2 ratio show that there is effective distribution of space in terms of the availability of resources and low competition between the species for better exploitation of the available resources. Conversely, high CGR and AGR recorded in the 3:1 ratio show effective acquisition of resources at cereal-dominated ratios.

Optimal spatial design helps achieve complementation through reduced competition for light, water, and nutrients, while non-optimal designs might lead to growth inhibition because of the nature of competition (Singh & Sarawgi, 1995; Lithourgidis et al., 2011). Variation in growth indices indicates that plant spatial pattern is an important parameter affecting growth and resource utilization (Yu et al., 2016).

4.4 Growth kinetics as mechanistic indicators of system performance

Indices like CGR, RGR, and AGR can be used as a strong basis for understanding how plants respond to management activities. Since these indices account for many physiological factors like photosynthesis, nutrient acquisition, and biomass production, they become excellent integrative measures for assessing system performance (Poorter et al., 2012; Watson, 1952; Hunt, 1990). From the results of the current study, one can deduce that growth kinetic parameters are greatly influenced by both organic nutrient management and cropping systems. Thus, the fact that the CGR and RGR indices were increased under an integrated organic farming regime signifies the high efficacy of physiological and nutrient-use efficiency processes. Furthermore, the interaction between nutrient management and cropping geometry reveals the effectiveness of using growth kinects as integrative parameters (Lambers et al., 2008). Thus, from the results obtained in the course of this research, we can see that our conceptual framework was confirmed since growth kinetics becomes an effective mechanism linking soil processes and plant physiology.

4.5 Implications for sustainable intensification

These findings show that the synergy between organic nutrient management and cereal-legume intercropping increases growth efficiency due to better nutrient synchronization and complementary resource use. Thus, such an innovative strategy might serve as one of the means of sustainable intensification that would decrease reliance on chemical fertilizer use while keeping or increasing crop yields. The positive effect observed in the kinetic behavior of plants proves the importance of synchronizing nutrients with their uptake and spatial organization to increase resource efficiency. The proposed practices are highly applicable in low external input systems, where the role of biological activities

is crucial for maintaining productivity and soil fertility (Lal, 2020; Glaze-Corcoran et al., 2020). Thus, the synergy between organic amendments and intercropping system optimization appears to be an effective biological method to increase growth efficiency.

4.6 Multivariate validation of growth responses

The output from the multivariate analysis demonstrates a combination of evidence for the effects of organic nutrients on the growth dynamics of crops. The high level of dominance displayed by the first principal component (PC1) at 93.1% of the variance suggests a strong relationship between growth dynamics and biomass characteristics through the same fundamental process, which is possibly related to nutrient availability and biological processes in the soil. The distinct separation between the controls and the integration groups demonstrates that organic nutrients play a critical role in altering ecosystem dynamics. The growth dynamics were poorer in the control due to poor nutrient recycling and microbial activity. Treatment of FYM + PM + Biofertilizer has an obvious position among other treatments, which suggests its increased effectiveness due to the combination of complementary nutrient sources and enhanced microbiological activity. Different organic treatments cluster into one group, which indicates that different combinations of organic fertilizers have similar effects because of their complementary functions. Vermicompost enhances the activities of microbial biomass and enzymes, resulting in greater nutrient availability (Arancon et al., 2004). High correlation between CGR, biomass accumulation, and branching indicates well-coordinated growth processes; increased nutrient availability leads to increased growth. Thus, the hypothesis of the regulation of growth dynamics by the organism itself in biological terms is confirmed. In general, the analysis of the correlation matrix through PCA proves the validity of the assumption concerning the enhancement of crop performance from the standpoint of their soil-plant interaction in terms of nutrients.

Correlation heatmap additionally proves that growth kinetics such as CGR, RGR, and AGR exhibit close positive correlations with biomass-associated characteristics. The linear dependencies between those growth kinetic values confirm that the crop growth processes are highly coordinated in nature. As nutrient content increases, there is a simultaneous increase in biomass and the structural elements associated with it. This shows that there is a physiological connection between those growth kinetics. It is noteworthy that the consistency in the strength of the relationship, regardless of treatment, demonstrates the involvement of systemic behavior, in which the benefits of organic management in nutrient content translate into improved biological functions rather than specific characteristics. The integration of biological behaviors is typical of biological regulatory mechanisms, where the activities of microorganisms in soils, the breakdown of nutrients, and their absorption by plants take place simultaneously.

5. Conclusion

In this experiment, one can clearly observe that the growth kinetics of the crops will be useful in coming up with a mechanism that will be helpful in assessing the effect of the nutrient management practices through the use of organic substances and crop intercropping on crop productivity. Furthermore, the inclusion of organic materials and microbial fertilizers showed very good growth responses in terms of CGR, RGR, and AGR, indicating the good relationship of nutrient utilization and crop nutrient requirements in biological organisms. In the various treatments, it was found out that the treatment using FYM along with poultry manure and microbial inoculants was found to have high growth responses, implying the fact that microbial nutrient dynamics are important for sustainable crop growth. Moreover, cereal-legume intercropping was also found to enhance these growth responses due to the interaction in the nutrients among these two organisms. The 2:2 ratio of wheat-chickpea intercropping provided the best growth responses during the early growth stage, while 3:1 ratio provided good growth responses during the latter stage. The strength and synchronization of the reaction of growth indexes proved by multivariate analysis prove that growth kinetics is a holistic method of describing the soil-plant interaction and its effect on agriculture. Moreover, unlike yield-focused evaluations, this study goes beyond such a paradigm and helps us understand how soil-plant interaction influences productivity. Thus, it is possible to view the synergies generated between organic nutrients absorption and improved intercropping as a way to enhance growth efficiencies without relying excessively on synthetic factors. Further research may include evaluating the whole system for an extended period of time in different environments as well as the application of growth kinetics with soil biology measures.

Declarations

Conflict of interest:

There is no conflict of interest between the authors

Permissions for plant collection

No wild plant species were collected for this study. Certified seeds of cultivated wheat and chickpea crops were obtained through institutional sources and used in accordance with institutional and national agricultural research guidelines.

Consent to publish:

Not applicable.

Consent to participate:

Not applicable.

Ethics approval:

All experimental research on plants, including the collection and use of plant materials, complied with relevant institutional, national, and international guidelines and legislation. The study involved only cultivated crop species, and no protected or endangered plant species were used.

Author Contribution

G.S.R. and S.M. conceptualized and designed the experiment. G.S.R., B.S., T.P. and I.S. conducted the field experiments and collected the data. A.K. performed the statistical and multivariate analyses and prepared the figures. G.S.R. and A.K. wrote the original draft of the manuscript. J.J. and S. contributed to data interpretation, visualization, and manuscript editing. All authors reviewed, revised, and approved the final version of the manuscript.

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Data availability

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

References

1. Adesemoye AO, Torbert HA, Kloepper JW. Plant growth-promoting rhizobacteria allow reduced application rates of chemical fertilizers. Microb Ecol. 2009;58:921–9.
2. Arancon NQ, Edwards CA, Atiyeh R, Metzger JD. Effects of vermicomposts produced from food waste on the growth and yields of greenhouse peppers. Bioresour Technol. 2004;93:139–44.
3. Banik P, Midya A, Sarkar BK, Ghose SS. Wheat and chickpea intercropping systems in an additive series experiment: advantages and weed smothering. Eur J Agron. 2006;24:325–32.
4. Bedoussac L, Journet EP, Hauggaard-Nielsen H, Naudin C, Corre-Hellou G, Jensen ES, Prieur L, Justes E. Ecological principles underlying the increase of productivity achieved by cereal–grain legume intercrops in organic farming. Agron Sustain Dev. 2015;35:911–35.
5. Bhattacharyya PN, Jha DK. Plant growth-promoting rhizobacteria (PGPR): emergence in agriculture. World J Microbiol Biotechnol. 2012;28:1327–50.
6. Blackman VH. The compound interest law and plant growth. Ann Botany. 1919;33:353–60.
7. Brooker RW, Bennett AE, Cong WF, Daniell TJ, George TS, Hallett PD, Hawes C, Iannetta PP, Jones HG, Karley AJ, Li L. Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. New Phytol. 2015;206:107–17.
8. Diacono M, Montemurro F. Long-term effects of organic amendments on soil fertility. Sustainable Agric. 2011;2:761–86.
9. Edmeades DC. The long-term effects of manures and fertilisers on soil productivity and quality: a review. Nutr Cycl Agrosyst. 2003;66:165–80.
10. Elfstrand S, Båth B, Mårtensson A. Influence of green manure amendment on soil microbial community composition and enzyme activity. Appl Soil Ecol. 2007;36:70–82.
11. Fujita K, Ofosu-Budu KG, Ogata S. Biological nitrogen fixation in mixed legume–cereal cropping systems. Plant Soil. 1992;141:155–75.
12. Geisseler D, Scow KM. Long-term effects of mineral fertilizers on soil microorganisms. Soil Biol Biochem. 2014;75:54–63.
13. Glaze-Corcoran S, Hashemi M, Sadeghpour A, Jahanzad E, Afshar RK, Liu X, Herbert SJ. Understanding intercropping to improve agricultural sustainability. Adv Agron. 2020;162:199–256.

14. Goyal S, Chander K, Mundra MC, Kapoor KK. Influence of inorganic fertilizers and organic amendments on soil organic matter and soil microbial properties under tropical conditions. Biol Fertil Soils. 1999;29:196–200.
15. Hauggaard-Nielsen H, Jensen ES. Facilitative root interactions in intercrops. Plant Soil. 2005;274:237–50.
16. Hayat R, Ali S, Amara U, Khalid R, Ahmed I. Soil beneficial bacteria and their role in plant growth promotion: a review. Ann Microbiol. 2010;60:579–98.
17. Hunt R. Basic growth analysis: plant growth analysis for beginners. Springer; 2012.
18. Lal R. Restoring soil quality to mitigate soil degradation. Sustainability. 2015;7:5875–95.
19. Lal R. Soil organic matter and its role in sustainable agriculture. J Soil Water Conserv. 2020;75:123–38.
20. Lambers H, Chapin FS, Pons TL. Plant physiological ecology. Springer; 2008.
21. Latati M, Dokukin P, Aouiche A, Rebouh NY, Takouachet R, Hafnaoui E, Hamdani FZ, Bacha F, Ounane SM. Species interactions improve biomass and land use efficiency in wheat–chickpea intercropping. Agronomy. 2019;9:765.
22. Li L, Tilman D, Lambers H, Zhang FS. Plant diversity and overyielding in intercropping systems. New Phytol. 2014;203:63–9.
23. Lithourgidis AS, Vasilakoglou IB, Dhima KV, Dordas CA, Yiakoulaki MD. Forage yield and quality in intercropping systems. Field Crops Res. 2006;99:106–13.
24. Lori M, Symnaczik S, Mäder P, De Deyn G, Gattinger A. Organic farming enhances soil microbial abundance. PLoS ONE. 2017;12:e0180442.
25. Louarn G, Bedoussac L, Gaudio N, Journet EP, Moreau D, Jensen ES, Justes E. Plant nitrogen nutrition in intercrops. Eur J Agron. 2021;124:126229.
26. Namvar A, Sharif R, Khandan T. Growth analysis and yield of chickpea under organic fertilization. Ekologija. 2011;57:1–8.
27. Nardi S, Pizzeghello D, Muscolo A, Vianello A. Physiological effects of humic substances on higher plants. Soil Biol Biochem. 2002;34:1527–36.
28. Philippot L, Raaijmakers JM, Lemanceau P, Van der Putten WH. The microbial ecology of the rhizosphere. Nat Rev Microbiol. 2013;11:789–99.
29. Poorter H, Garnier E. Ecological significance of inherent variation in relative growth rate and its components. Functional Plant Ecology. CRC; 2007. pp. 67–100.
30. Poorter H, Niklas KJ, Reich PB, Oleksyn J, Poot P, Mommer L. Biomass allocation patterns in plants. New Phytol. 2012;193:30–50.
31. Rudresh DL, Shivaprakash MK, Prasad RD. Combined application of biofertilizers on chickpea growth. Appl Soil Ecol. 2005;28:139–46.
32. Shaji H, Chandran V, Mathew L. (2021). Organic fertilizers as controlled nutrient sources. In: *Controlled Release Fertilizers for Sustainable Agriculture*. pp. 231–245.
33. Six J, Frey SD, Thiet RK, Batten KM. Bacterial and fungal contributions to carbon sequestration in agroecosystems. Soil Sci Soc Am J. 2006;70:555–69.
34. Tuck SL, Winqvist C, Mota F, Ahnström J, Turnbull LA, Bengtsson J. Organic farming and biodiversity. J Appl Ecol. 2014;51:746–55.
35. Vanlauwe B, Descheemaeker K, Giller KE, Huising J, Merckx R, Nziguheba G, Wendt J, Zingore S. Integrated soil fertility management. Soil. 2015;1:491–508.
36. Vessey JK. Plant growth promoting rhizobacteria as biofertilizers. Plant Soil. 2003;255:571–86.
37. Watson DJ. The physiological basis of variation in yield. Adv Agron. 1952;4:101–45.
38. Willey RW. Intercropping: Its importance and research needs. Field Crop Abstracts. 1979;32:1–10.
39. Yu Y, Stomph TJ, Makowski D, van der Werf W. Temporal niche differentiation in intercropping. Field Crops Res. 2015;184:133–44.
40. Zhang F, Li L. Using competitive and facilitative interactions in intercropping systems enhances crop productivity and nutrient-use efficiency. Plant Soil. 2003;248:305–12.

Tables

Table 1. Effect of cropping geometry and integrated organic nutrient management on crop growth rate (CGR), relative growth rate (RGR), and absolute growth rate (AGR) of wheat during different growth intervals. Values represent mean of three replications. SEm ± denotes standard error of mean, and CD (p = 0.05) indicates the least significant difference at 5% probability level. FYM = farmyard manure; VC = vermicompost; PM = poultry manure; DAS = days after sowing.

(A) Effect of cropping geometry (Factor 1)

Cropping system	CGR			RGR			AGR		
	0–30 DAS	30–60 DAS	60–90 DAS	0–30 DAS	30–60 DAS	60–90 DAS	0–30 DAS	30–60 DAS	60–90 DAS
Sole wheat	0.140	0.643	4.004	0.047	0.056	0.054	0.818	0.782	0.893
2:2 Wheat + chickpea	0.156	0.795	4.138	0.051	0.060	0.059	0.778	0.767	0.967
3:1 Wheat + chickpea	0.151	0.708	4.944	0.050	0.058	0.061	0.802	0.721	1.012
SEm ±	0.002	0.002	0.003	0.000	0.000	0.000	0.004	0.006	0.004
CD (p = 0.05)	0.004	0.005	0.008	0.001	0.002	0.001	0.017	0.024	0.017

(B) Effect of organic nutrient treatments (Factor 2)

Treatment	CGR			RGR			AGR		
	0–30 DAS	30–60 DAS	60–90 DAS	0–30 DAS	30–60 DAS	60–90 DAS	0–30 DAS	30–60 DAS	60–90 DAS
Control	0.115	0.594	1.961	0.041	0.041	0.044	0.761	0.674	0.938
FYM 10 t ha^{-1} + VC 6 t ha^{-1} + Azotobacter + PSB	0.156	0.663	4.706	0.051	0.055	0.064	0.818	0.759	0.958
FYM 5 t ha^{-1} + PM 2 t ha^{-1} + Azotobacter + PSB	0.173	0.842	5.337	0.055	0.059	0.062	0.829	0.787	0.947
VC 3 t ha^{-1} + PM 2 t ha^{-1} + Azotobacter + PSB	0.154	0.762	5.446	0.051	0.059	0.064	0.789	0.807	0.957
SEm ±	0.002	0.002	0.004	0.000	0.000	0.000	0.007	0.007	0.004
CD (p = 0.05)	0.005	0.006	0.009	0.002	0.001	0.002	0.020	0.022	0.013

Table 2. Effect of cropping geometry and integrated organic nutrient management on plant height, dry matter accumulation, and branching characteristics of chickpea at different growth stages. Values represent the mean of three replications. SEm ± denotes the standard error of the mean, and CD (p = 0.05) indicates the least significant difference at 5% probability level. FYM = farmyard manure; VC = vermicompost; PM = poultry manure; DAS = days after sowing.

(A) Effect of cropping geometry (Factor 1)

Cropping system	Plant height (cm $plant^{-1}$)				Dry weight (g $plant^{-1}$)			Branches $plant^{-1}$				
	30 DAS	60 DAS	90 DAS	Harvest	30 DAS	60 DAS	90 DAS	Primary (30 DAS)	Primary (60 DAS)	Secondary (60 DAS)	Secondary (90 DAS)	Tertiary
2:2 Wheat + chickpea	12.51	20.64	43.80	73.38	0.329	0.586	2.830	2.664	3.303	4.108	7.774	3.663
3:1 Wheat + chickpea	12.32	20.73	47.30	73.57	0.270	0.517	2.438	2.693	3.469	4.135	7.580	4.441
SEm ±	0.030	0.053	0.039	0.052	0.004	0.006	0.039	0.058	0.051	0.052	0.087	0.112
CD (p = 0.05)	0.121	0.214	0.158	0.209	0.018	0.024	0.158	0.232	0.206	0.210	0.349	0.452

(B) Effect of organic nutrient treatments (Factor 2)

Treatment	Plant height (cm plant⁻¹)				Dry weight (g plant⁻¹)			Branches plant⁻¹				
	30 DAS	60 DAS	90 DAS	Harvest	30 DAS	60 DAS	90 DAS	Primary (30 DAS)	Primary (60 DAS)	Secondary (60 DAS)	Secondary (90 DAS)	Tertiary
Control	11.61	19.85	43.17	68.91	0.228	0.473	1.815	2.110	2.550	2.940	5.770	2.270
FYM 10 t ha⁻¹ + VC 6 t ha⁻¹ + Azotobacter + PSB	12.76	20.94	46.79	75.54	0.320	0.570	2.892	2.600	3.660	4.160	8.220	4.490
FYM 5 t ha⁻¹ + PM 2 t ha⁻¹ + Azotobacter + PSB	12.54	21.37	46.89	77.22	0.328	0.588	2.828	2.990	3.660	4.940	8.710	5.100
VC 3 t ha⁻¹ + PM 2 t ha⁻¹ + Azotobacter + PSB	12.75	20.62	45.44	72.23	0.321	0.567	3.001	2.990	3.660	4.440	7.990	4.330
SEm ±	0.057	0.035	0.032	0.046	0.004	0.009	0.024	0.058	0.060	0.068	0.123	0.099
CD (p = 0.05)	0.170	0.103	0.095	0.137	0.018	0.027	0.073	0.232	0.181	0.203	0.370	0.298

Table 3. Effect of cropping geometry and integrated organic nutrient management on plant height, tiller number, and dry matter accumulation of wheat at different growth stages. Values represent mean of three replications. SEm ± denotes standard error of mean, and CD (p = 0.05) indicates the least significant difference at 5% probability level; NS = non-significant. FYM = farmyard manure; VC = vermicompost; PM = poultry manure; DAS = days after sowing.

A) Effect of cropping geometry (Factor 1)

Cropping system	Plant height (cm plant⁻¹)				Tillers plant⁻¹			Dry weight (g plant⁻¹)		
	30 DAS	60 DAS	90 DAS	Harvest	30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS
Sole wheat	24.639	47.967	74.029	88.816	1.829	3.247	3.690	0.210	1.174	7.328
2:2 Wheat + chickpea	23.346	46.100	75.418	89.517	2.135	3.913	4.524	0.243	1.427	7.480
3:1 Wheat + chickpea	24.208	45.776	76.216	89.538	1.970	3.636	4.634	0.231	1.288	8.710
SEm ±	0.070	0.090	0.161	0.066	0.061	0.055	0.026	0.003	0.001	0.107
CD (p = 0.05)	0.281	0.391	0.649	0.266	NS	0.223	0.104	0.011	0.069	0.430

(B) Effect of organic nutrient treatments (Factor 2)

Treatment	Plant height (cm plant⁻¹)				Tillers plant⁻¹			Dry weight (g plant⁻¹)		
	30 DAS	60 DAS	90 DAS	Harvest	30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS
Control	22.896	43.002	72.488	83.669	1.293	2.627	3.217	0.172	1.062	3.999
FYM 10 t ha⁻¹ + VC 6 t ha⁻¹ + Azotobacter + PSB	24.597	47.109	76.432	90.230	2.108	3.662	4.551	0.234	1.229	8.290
FYM 5 t ha⁻¹ + PM 2 t ha⁻¹ + Azotobacter + PSB	24.868	48.782	77.476	91.336	2.440	4.072	4.627	0.259	1.521	9.538
VC 3 t ha⁻¹ + PM 2 t ha⁻¹ + Azotobacter + PSB	23.898	47.563	75.822	91.927	2.071	4.033	4.737	0.246	1.373	9.530
SEm ±	0.091	0.156	0.116	0.080	0.050	0.066	0.074	0.004	0.018	0.106
CD (p = 0.05)	0.273	0.467	0.348	0.240	0.149	0.198	0.223	0.013	0.055	0.317

Table 4. Effect of cropping geometry and integrated organic nutrient management on crop growth rate (CGR), relative growth rate (RGR), and absolute growth rate (AGR) of chickpea during different growth intervals. Values represent the mean of three replications. SEm ± denotes the standard error of the mean, and CD (p = 0.05) indicates the least significant difference at 5% probability level. FYM = farmyard manure; VC = vermicompost; PM = poultry manure; DAS = days after sowing.

(A) Effect of cropping geometry (Factor 1)

Cropping system	CGR (g m⁻² day⁻¹)			RGR (g g⁻¹ day⁻¹)			AGR (cm day⁻¹)		
	0–30 DAS	30–60 DAS	60–90 DAS	0–30 DAS	30–60 DAS	60–90 DAS	0–30 DAS	30–60 DAS	60–90 DAS
2:2 Wheat + chickpea	0.110	0.086	0.748	0.039	0.019	0.052	0.417	0.271	0.773
3:1 Wheat + chickpea	0.090	0.083	0.641	0.032	0.022	0.050	0.411	0.280	0.886
SEm ±	0.001	0.010	0.001	0.000	0.000	0.000	0.000	0.000	0.000
CD (p = 0.05)	0.002	0.001	0.005	0.001	0.001	0.001	0.002	0.003	0.003

(B) Effect of organic nutrient treatments (Factor 2)

Treatment	CGR (g m⁻² day⁻¹)			RGR (g g⁻¹ day⁻¹)			AGR (cm day⁻¹)		
	0–30 DAS	30–60 DAS	60–90 DAS	0–30 DAS	30–60 DAS	60–90 DAS	0–30 DAS	30–60 DAS	60–90 DAS
Control	0.076	0.082	0.447	0.027	0.015	0.045	0.388	0.274	0.778
FYM 10 t ha⁻¹ + VC 6 t ha⁻¹ + Azotobacter + PSB	0.107	0.086	0.772	0.038	0.019	0.054	0.425	0.273	0.862
FYM 5 t ha⁻¹ + PM 2 t ha⁻¹ + Azotobacter + PSB	0.110	0.087	0.747	0.039	0.019	0.052	0.418	0.294	0.851
VC 3 t ha⁻¹ + PM 2 t ha⁻¹ + Azotobacter + PSB	0.107	0.082	0.811	0.039	0.020	0.055	0.425	0.262	0.828
SEm ±	0.001	0.020	0.001	0.000	0.001	0.000	0.001	0.000	0.001
CD (p = 0.05)	0.002	0.001	0.003	0.001	0.001	0.002	0.002	0.001	0.002

Figures

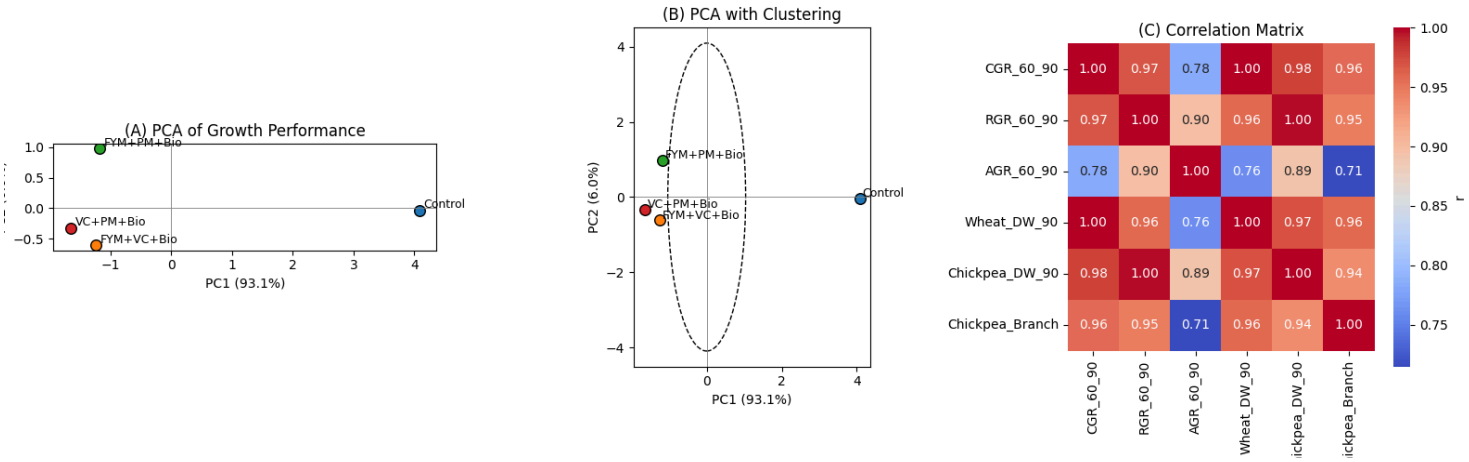


Figure 1

Multivariate analysis of growth kinetics and biomass traits under different organic nutrient management treatments.
(A) Principal component analysis (PCA) showing the distribution of treatments based on growth performance, where PC1 and PC2 explained 93.1% and 6.0% of total variance, respectively.; (B) PCA with clustering ellipse highlighting the grouping of organic treatments and separation from the control.; (C) Correlation heatmap illustrating strong positive relationships among crop growth rate (CGR), relative growth rate (RGR), absolute growth rate (AGR), biomass accumulation, and branching traits, indicating coordinated regulation of growth processes under integrated nutrient management.

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