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PHENOLOGY, CROP STAND, AND DRY MATTER PRODUCTION OF WHEAT IN RESPONSE TO BENEFICIAL MICROBES AND ORGANIC MATTER SOURCES

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SUMMARY

Adding organic matter to soil proved an efficient strategy for restoring soil fertility and improving crop dry matter - an indicator of yield potential. In this regard, evaluating the sources of organic matter (OM) (control, poultry manure [PM], farmyard manure [FYM], compost, and mungbean residues [MR]) to provide 120 kg N ha^{-1} and effective microbes (EM) (0, 100, 200, and 300 L ton^{-1} of OM) as 2% solution proceeded in field conditions during 2017–2019. The sowing of wheat seeds (cv. Pirsabak 2015) at 120 kg ha^{-1} took place in the field using RCB design with four replications. Results showed that PM/FYM had delayed the phenology and improved the biomass-related parameters, dry matter (DM) accumulation, and crop growth rate (CGR) more than compost and MR. However, the results were more pronounced when applied with 300 L EM ton^{-1} of OM from the PM. The maximum DM (55%) accumulation in plant parts occurred beyond 100 days after sowing (DAS). A marked increase in DM and CGR beyond 60 DAS and a reduction in CGR beyond 120 DAS appeared irrespective of treatments. In the case of EM, the 300 L ton^{-1} revealed superior in terms of growth, DM accumulation, CGR, and delayed phenology. Structural equation modeling suggested that DM production gained a direct effect from crop phenology (46.1%) and crop stand (30.4%) but no indirect effect from crop growth (24.8%). In conclusion, the 300 L EM ton^{-1} of OM applied to PM or FYM had improved the crop stand, development, and DM production in wheat.

Keywords: Wheat, structural equation model, poultry/farmyard manure, compost, mungbean residues, effective microbes, crop growth

Key findings: Phenology was delayed using PM and FYM, thereby increasing the plant growth and dry matter accumulation over compost and MR. Improved DM and CGR resulted from PM, FYM, and MR with higher levels of 300 L ton^{-1} of OM versus compost with a lower level of EM (100 L ton^{-1} of OM). More than 50% of dry matter accumulation occurs after spikes emergence. DM production was directly affected by crop phenology (46.1%) and crop stand (30.4%) but indirectly affected by crop growth (24.8%).

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INTRODUCTION

Excessive and injudicious uses of synthetic/chemical fertilizers caused soil degradation and altered the environmental balance and nutrient dynamics, reducing soil fertility (Akhtar *et al.*, 2020; Wang *et al.,* 2020). The reduction in soil fertility needs replenishing with the help of supplying organic matter from external sources for future sustainability (Muhammad *et al.,* 2018; Akhtar *et al.,* 2019a; Bome *et al*., 2022). Adding soil organic matter (SOM) is confirmed as an important indicator for improving crop productivity and soil sustainability by altering nutrient dynamics and soil physio-chemical and biological properties (Akhtar *et al.,* 2018; Kong *et al.,* 2019; Wang *et al.,* 2020). Improving soil organic matter and ultimate soil fertility can result from adopting various soil and crop management techniques, including adding organic manures like compost, farmyard manure, poultry manure, and legume residues (Khan *et al.,* 2015; Muhammad *et al.,* 2018). However, the bulk usage and on-time release of nutrients via the decomposition of manures is a critical problem (Rasul *et al.,* 2015). Thus, stimulating the decomposition of organic matter using proper soil amendments like effective microbes would enable the farmers to utilize these manures more effectively for higher crop production (Khan *et al.,* 2015; Swailam *et al*., 2021; Adnan *et al.,* 2022).

Using beneficial microbes as a stimulator for decomposing organic matter is an essential management tool for enhancing crop productivity and soil sustainability. Effective microbes, when applied to the soil, increase the mineralization rate and release balance nutrition for plant growth (Iriti *et al.,* 2019). It mainly favors the production of different enzymes, thereby enhancing the population and activities of existing microflora in the soil-plant system (Hidalgo *et al.,* 2022). In addition, the hydrolytic enzymes released by beneficial microbes break down the recalcitrant portion of organic molecules that improves soil sustainability (Talaat *et al.,* 2015; Joshi *et al.,* 2019). The soil microbial biomass highly regulates soil enzymatic activities and influences nutrient transformation and soil quality (Rena *et al.,* 2019). The main reason for these effects is that the photosynthetic bacteria, the main constituents of microbial culture, show synergistic work with other microorganisms to sustain the plant's nutritional requirements and reduce the incidence of pathogenic microorganisms (Hidalgo *et al.,* 2022). Furthermore, effective microorganisms promote manure efficiency and improve soil fertility and nutrient uptake, photosynthesis, plant growth, environmental quality, and crop yield (Chen *et al.,* 2018; Joshi *et al.,* 2019).

The balance nutrients provision, especially N, increased the leaf area duration (Akhtar *et al.,* 2019b), delayed the leaf senescence, and enhanced the dry matter (DM) production (Alamzeb *et al.,* 2018). Dry matter accumulation is a promising indicator for optimum yield as the pre-anthesis biomass accumulation efficiently contributes to grain filling (Moe *et al.,* 2019). Thus, there is a dire need to improve DM accumulation at various growth stages to enhance crop productivity. Plant photosynthetic capacity is a vital indicator for improving dry matter yield. Similarly, the balance of nutrient availability and enriched soil fertility via the OM enhanced the plant's photosynthetic capacity and, consequently, the dry matter accumulation (Alamzeb *et al.,* 2018; Akhtar *et al.,* 2019b). Bases of previous studies on growth and DM predominantly centered on stresses or simply recorded at heading and maturity (Alamzeb *et al.,* 2018). However, studies on DM accumulation over time, especially with OM and EM, revealed little documentation.

Therefore, the objectives of the recent study sought to determine the suitable source of organic matter for improving wheat growth and dry matter production and to quantify the optimum level of effective microbes for improving manure decomposition and wheat growth. Finding the interactive response of OM and EM for improving wheat biomass is also part of the current experiment. Knowledge of the relationship between stimulated manure decomposition and dry matter partitioning at different growth stages could help develop high-yielding wheat genotypes under diverse environmental conditions.

MATERIALS AND METHODS

Experimental site and weather details

The experiment happened at the experimental station of The University of Agriculture, Peshawar, Pakistan (34° 02′N and 71° 48′E latitude and 331 m altitude). Meteorological data of the experimental site during the study period appear in Figure 1. The textural class of soil was silt loam (up to 30 cm depth) based on its composition of sand (20.16%), silt (70.21%), and clay (9.63%), slightly alkaline nature (pH, 8.65) with EC and bulk density of

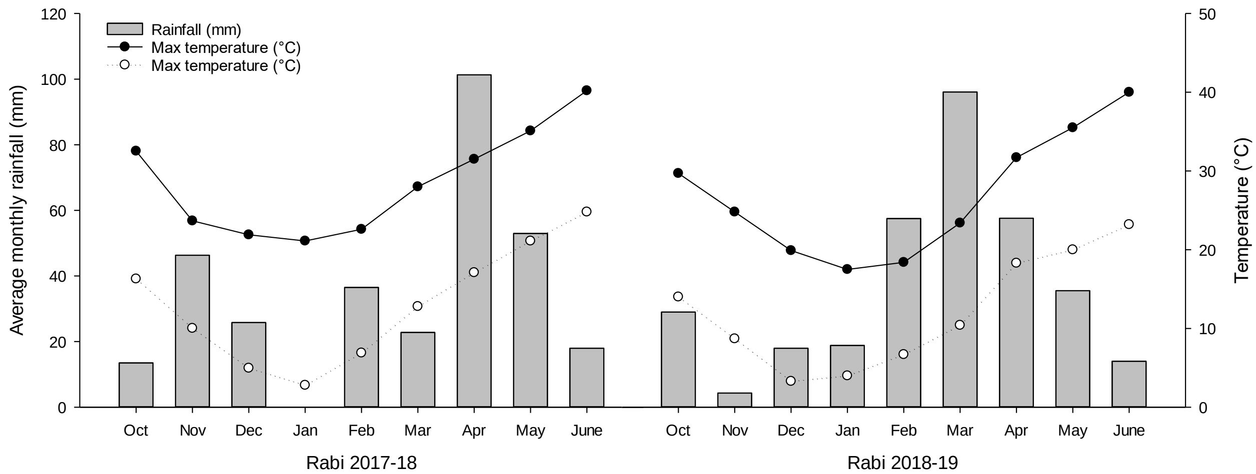

Figure 1. Rainfall (mm), temperature maximum (Max °C), and temperature minimum (Man °C) of the study area during rabi-2018 and rabi-2019.

Table 1. Physico-chemical properties of soil and organic materials used in the experiment.

Physico-chemical properties	Unit	Soil	FYM	PM	Compost	MR
Organic carbon	%	0.45	15.8	18.58	12.32	65.82
Total nitrogen	%	0.04	1.2	2.0	2.0	2.25
Mineral nitrogen	mg kg^{-1}	12.9	-	-	-	-
pH	-	8.65	6.9	6.4	7.1	7.3
Electrical conductivity	dS m^{-1}	1.92	-	-	-	-
Phosphorous	mg kg^{-1}	3.78ꝉ	0.7	1.9	0.38	0.45
Potash	mg kg^{-1}	103ꝉ	0.10	1.2	1.32	0.37
Bulk density	g cm^{-3}	1.28	-	-	-	-
Sand	%	20.16	-	-	-	-
Silt	%	70.21	-	-	-	-
Clay	%	9.63	-	-	-	-
Textural class	-	Silt loam				

ꝉAB-DTPA extractable; MR: Mungbean residues; FYM/PM: Farmyard/poultry manure.

1.92 dS m^{-1} and 1.48 g cm^{-3}, respectively (Table 1). The soil of the experimental site was poor in organic carbon (0.35%), total N (0.04 g kg^{-1} soil), AB-DTPA extractable P, and K (3.78 and 1.08 mg kg^{-1} soil, respectively).

Experimental design and treatments

The field experiment employed a randomized complete block design with four replications having a plot size of 15 m^2. The experiments included two factors, i.e., a) organic matter (OM) sources (control, poultry manure [PM], farmyard manure [FYM], compost, and mungbean residues [MR]) to supply a total of 120 kg N ha^{-1} and b) effective microbes (0, 100, 200, and 300 L ton^{-1} of OM). Poultry and farmyard manure sources were the Dairy Farm, The University of Agriculture, Peshawar. Meanwhile, the legume residues came from the Agronomy Research Farm, The University of Agriculture, Peshawar. However, compost (Magic grow) and EM purchases took place from the local market. The EM supply came from "Bioabb," a commercial product of NFRDF NGO prepared in collaboration with the Faculty of Agriculture, The University of Agriculture Faisalabad. The bioabb consists of 1×10^{11} cfu ml^{-1} lactic acid bacteria (*Lactobacillus casei, Streptococcus lactis, Lactobacillus, plantarum*), 1×10^6 cfu ml^{-1} photosynthetic bacteria (*Rhodopseudomona palustris*, *Rhodobacter sp.*), 1×10^5 cfu ml^{-1} fermenting fungi (*Aspergillus oryzae, Mucor heimalis*), 1×10^3 cfu ml^{-1} yeast (*Saccharomyces griesus*), and molasses as media. The 2% solution of EM prepared by mixing 20 ml bioabb in 980 ml distilled water was properly mixed with OM in various proportions and applied respectively. The analysis of PM, FYM, and MR for total nitrogen (N), P, K, organic C, pH, and EC with detailed information occurred in Table 1.

Crop husbandry

The OM and EM mixtures were in various combinations, then applied to their respective plots about 30 days before sowing. The MR, finely chopped at 3–5 cm, used the cutting machine before incorporation. The parcels receiving no OM received EM in amounts equal to the average of its corresponding level applied to each type of OM. After applying the treatments, plowing ensued with a common cultivator, with the field irrigated and the layout fixed with the help of corner points for future management. The calculated P and K added to OM had the remaining amounts supplied at the time of sowing from SSP and MOP at the rate of 90 and 60 kg ha^{-1}, respectively. Preparing the field for sowing used a regular cultivator, followed by a rotavator. Sowing of the wheat (cv. Pirsabak 2015) proceeded at the seed rate of 120 kg ha^{-1} in 10 rows, 30 cm apart, using a drill machine during the first weeks of November 2017 and 2018. Sowing the maize cultivar (Azam) was at the seed rate of 30 kg ha^{-1} in 2018 as a gap crop between two consecutive wheat crops using the same treatment structure. The sowing depth was constant at 5 cm, with planting made employing a planter machine in four rows, 3 m long and 75 cm apart, using standard cultural practices. Wheat received five irrigations, while eight to maize according to the crop needs. During the growing season, manual weeding took place to keep weeds below the economic threshold.

Observation and measurements

During the growing season, a random collection of five soil samples progressed up to 30 cm depth from the experimental field before treatment addition. The samples, thoroughly mixed into a composite, gained further analysis in the laboratory. The fresh soil samples used determined the soil mineral nitrogen; the remaining soil underwent drying in an oven at 70 °C, finely ground with a grinder machine of 2 mm mesh size, then stored for TN, SOC, pH, and EC for analysis using standard procedures. Soil total N measurement employed the Kjelflex K360 (Buschi, Switzerland) nitrogen analyzer.

Phenology determination was in terms of days from sowing till 50% completion of respective growth stages (booting, anthesis, and physiological maturity), with the yellowing of plants considered a criterion for determining physiological maturity. Recording the emergence and tillers m^{-2} was by counting the number of seedlings/tillers with the help of a meter rod at different locations in three central rows and then converted to emergence/tillers m^{-2}. Determining leaf area $tiller^{-1}$ was at the anthesis stage from five randomly selected tillers, with the length and width of all leaves from the five tillers measured. Measuring the leaf length was the distance between the base and tip of the leaf, whereas the leaf width measurement was at three different locations (base, middle, and tip), then averaged. The average leaf length and width were multiplied with 0.69 as the correction factor, with the leaf area $tiller^{-1}$ worked out by multiplying the average leaf area with an average number of leaves $tiller^{-1}$. Recording of the plant height as the distance between the base of the plant near the soil to the tip of the spike, excluding the awns, used a meter rod. Dry matter accumulation determination was by cutting 1 m side row from each plot at 20, 40, 60, 80, 100, 120, 140, and 160 DAS. The samples, well tagged, attained air drying for one day, then kept in an oven at 70 °C for 72 h till the materials dried completely. Weighing the samples with a digital electronic balance, working out the conversion to dry matter m^{-2} followed. The crop growth rate (CGR) calculation uses the following formula.

$$\mathbf{CGR\ (g\ m^{-2}day^{-1}) = \frac{W2 - W1}{T2 - T1} \times \frac{1}{GA}}$$

W2 - W1 is the difference in DM weight between the final and initial interval and T2 - T1 is the difference in the time interval between two consecutive samplings.

Statistical analysis

Employing a three-way ANOVA appropriate for RCB design tested the effect of time (year), OM, EM, and their interaction on phenology, crop stand establishment, DM, and CGR. Comparison of means used the least significant differences (LSD) test at $P \leq 0.05$. The statistical analyses employed Statistix, version 8.1 software (Informer Technologies Inc.), with figures made using Sigma Plot, version 12.5 (Systat Software Inc., USA). Structural equation model development was with R-Software v-4.2.2 (R Core Team, 2022) to clarify the relationships among the a) crop phenological observation (P_O), i.e., days to boot stage (DBS), days to anthesis (DTA), days to physiological maturity (DPM), b) crop stand (C_S), i.e., emergence m^{-2} (EMG) and tiller m^{-2} (TILL), c) crop growth (C_G), i.e., leaf area (LA), plant height (PH), crop growth rate (CGR), and dry matter (DM) production. The model fit observed was from the $\chi 2$ test (> 0.05), the goodness-of-fit (GFI) test > 0.95, the comparative fit index (CFI) > 0.90, and the root square mean error of approximation (RMSEA) < 0.08.

RESULTS

Phenological observations

Statistical analysis for days to phenological growth stages (booting, anthesis, and physiological maturity) showed pronounced variations for OM and EM during 2017–2018 and 2018–2019 (Figure 2). Treatment addition during the second year, except compost, has delayed all the phenological growth stages more than during the first year (Figure 2). The main effects of OM and EM revealed significance ($P \leq 0.05$) for all phenological durations in the first and second years. However, their interaction showed significance only for days to physiological maturity during 2017–2018. Results indicated that PM, followed by FYM, had increased the days for completing phenological growth stages over compost and MR. Furthermore, during the first year, no significant differences occurred in the number of days for completing phenological growth stages with compost and MR. However, the following year, the MR delayed the phenology of the compost. In the case of EM, the higher levels (300 L ton^{-1} of OM) had deferred the phenological stages compared with the lower levels of EM across the years. However, no significant differences in phenological observations showed between 200 and 300 L EM ton^{-1} of OM with repeated application during the second year. The OM × EM interaction for days to physiological maturity (Figure 3a) revealed that the addition of PM and MR had increased the days to physiological maturity with increasing levels of EM from 100 to 300 L ton^{-1}. A similar trend also appeared for FYM treatment up to 200 L EM ton^{-1} of OM; however, a further increase of EM to 300 L ton^{-1} did not significantly affect the days to physiological maturity.

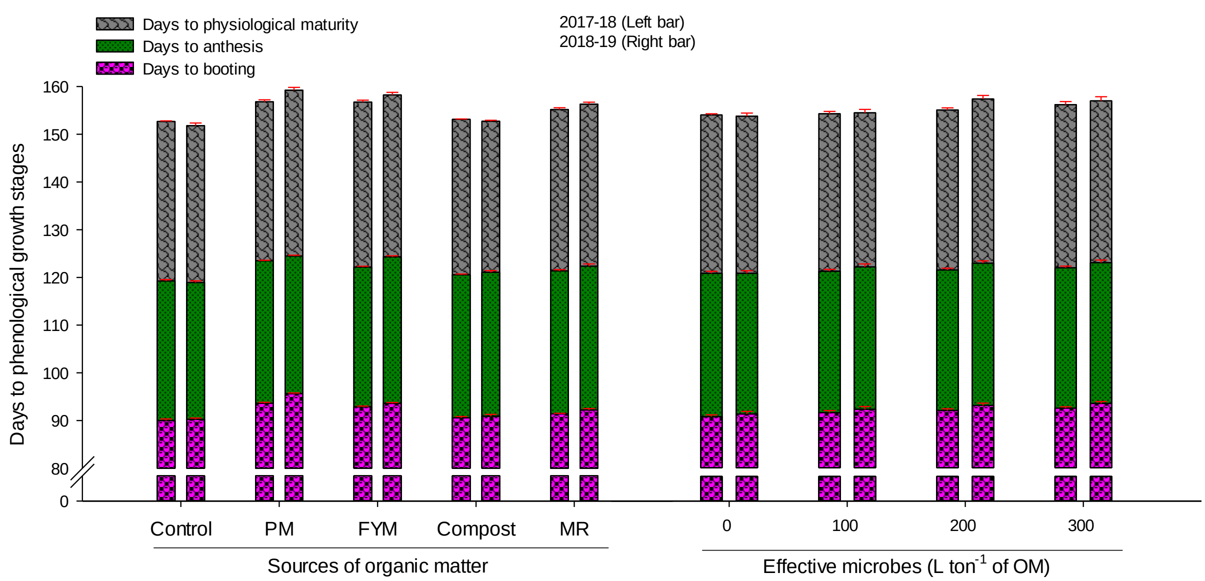

Figure 2. Phenology (days to booting, days to anthesis, and days to physiological maturity) of wheat in response to sources of organic matter and levels of effective microbes. The vertical bars (red color) represent the standard error of means. PM: Poultry manure, FYM: Farmyard manure, MR: Mungbean residues.

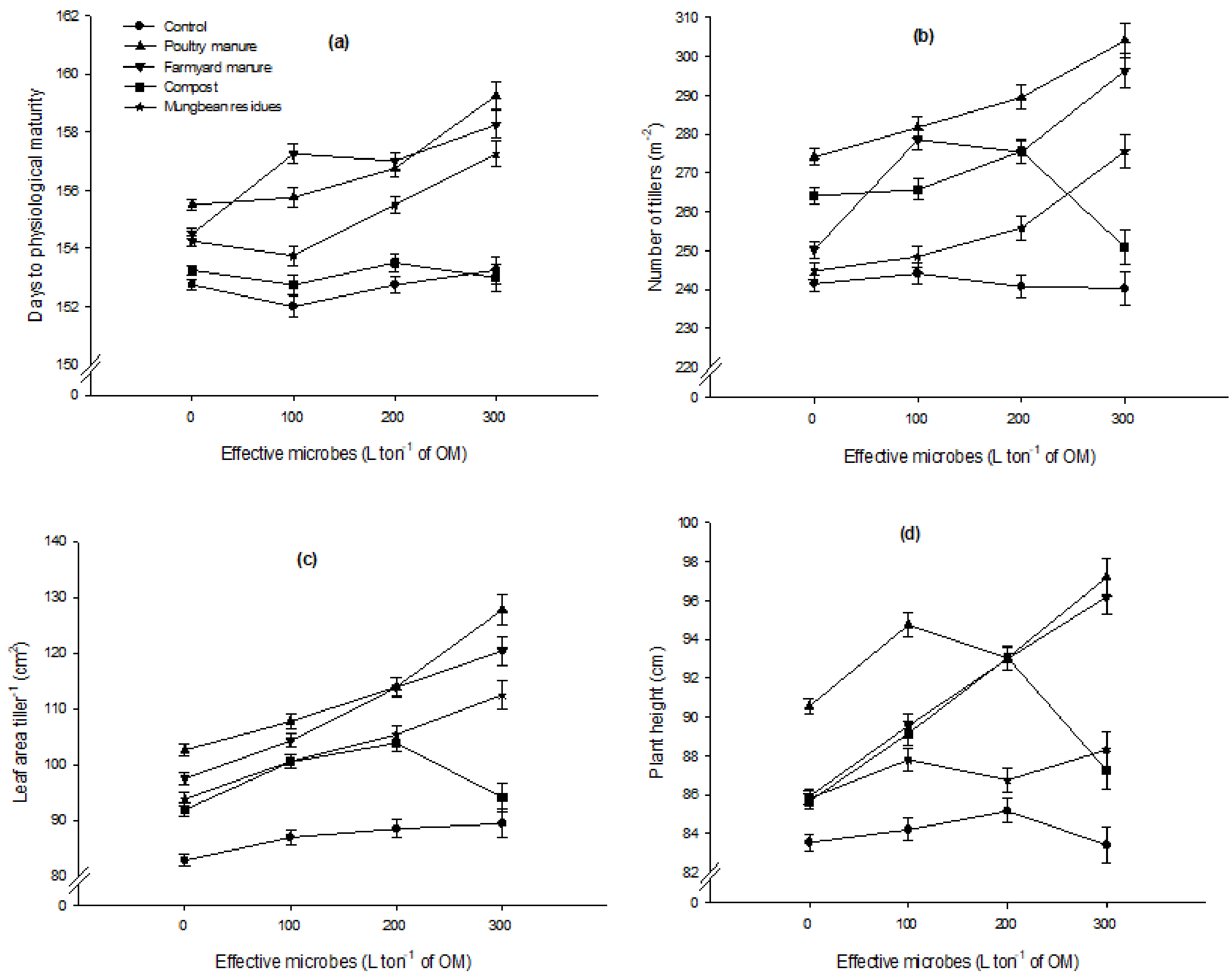

Figure 3. Interactive response of OM × EM for a) days to physiological maturity, b) the number of tillers m^{-2}, c) leaf area $tillers^{-1}$, and d) plant height. The vertical bars represent the standard error of means.

Plant stand and biomass

Emergence and tillers m^{-2} of wheat were significantly higher during the second year compared with the first year (Table 2). The OM brought about significant variations ($P \leq 0.05$) in emergence and tillers m^{-2} during both years (2017–2018 and 2018–2019), while EM was found significant only during the second year. The emergence of m^{-2} with PM, FYM, and compost was statistically similar but higher than MR and control during both years. Likewise, a higher number of tillers m^{-2} over control occurred with PM (18% and 20%) and FYM (12% and 16%) than MR (12% and 10%) and compost (9% each) during the first and second years, respectively. Additionally, the tillers m^{-2} observed with PM and FYM, as well as, MR and compost, were statistically non-significant. The EM, irrespective of its levels, had increased the emergence and tillers m^{-2} over no EM treatment. However, the values were comparatively higher with 300 L EM ton^{-1} of OM than other levels. The OM × EM interaction (Figure 3b) plotted against average data showed no significant changes in control with increasing levels of EM, whereas, the PM, FYM, and MR treatments at 300 L EM ton^{-1} of OM had increased the number of tillers m^{-2} over control by 10.9%, 18.4%, and 12.6%, respectively. Moreover, the number of tillers m^{-2} in PM and FYM treatment was significantly higher than the MR treatment across all levels of EM.

Table 2. Emergence m^{-2}, tillers m^{-2}, leaf area $tiller^{-1}$ and plant height of wheat as affected by sources of organic matter (OM) and levels of effective microbes (EM) during 2017-2019.

Treatments	Emergence m^{-2}		Tillers m^{-2}		Leaf area $tiller^{-1}$ (cm^2)		Plant height (cm)	
	2017-18	2018-19	2017-18	2018-19	2017-18	2018-19	2017-18	2018-19
120 kg N ha^{-1} from OM								
Control	121 b	118 c	241 d	242 c	89.8 d	87.0 d	84.1 d	84.5 d
PM	133 a	139 a	285 a	290 a	108.1 a	113.1 a	93.9 a	94.4 a
FYM	131 a	137 a	270 b	281 a	102.0 b	109.0 a	91.2 b	93.3 ab
Compost	130 a	132 ab	262 bc	266 b	96.7 bc	97.6 c	88.8 c	88.9 c
MR	124 b	130 b	249 cd	264 b	95.1 cd	103.1 b	87.2 c	90.8 bc
$LSD_{0.05}$	6	5	14.0	13.6	5.6	5.2	2.2	3.0
EM (L ton^{-1} of OM)								
0	125 a	126 b	254 a	256 b	93.0 c	93.8 c	86.3 b	87.8 b
100	128 a	130 ab	259 a	269 a	96.7 bc	100.1 b	89.1 a	89.7 ab
200	129 a	132 a	264 a	271 a	100.4 ab	105.1 a	90.2 a	91.8 a
300	130 a	136 a	267 a	280 a	103.3 a	108.9 a	90.5 a	92.2 a
$LSD_{0.05}$	NS	4	NS	12.1	5.1	4.6	1.9	2.7
Means	128 b	131 a	261 b	269 a	98.3 a	102.0 b	89.0 a	90.4 a
OM × EM	NS	NS	*	**	NS	*	*	NS

"*" Significant at $P \leq 0.05$; "**" Significant at $P \leq 0.01$; "NS" Non-significant, levels of EM were added as 2% solution, PM: poultry manure, FYM: farmyard manure, MR: mungbean residues.
Means followed by a different letter (s) within the same group in each category were statistically significant using LSD≤0.05.

Leaf area $tiller^{-1}$ was significantly higher during the second year (102 cm^2) as compared to the first year (98.3 cm^2) (Table 2). During 2017–2018, all sources of OM had increased the leaf area $tiller^{-1}$ over control. However, the increase was more pronounced (1.2 times) with PM. In the case of EM, a significant ($P \leq 0.05$) increase in leaf area $tiller^{-1}$ over 0 L ton^{-1} resulted with 300 L ton^{-1} (11%) that further increased (11%) with a higher level (300 L ton^{-1}). During 2018–2019, the leaf area $tiller^{-1}$ observed with PM (113.1 cm^2) and FYM (109 cm^2) was statistically comparable but higher than the compost (97.6 cm^2), MR (103.1 cm^2), and control treatments (87 cm^2). In the case of EM, the leaf area $plant^{-1}$ ranged from 93.8 to 108.9 cm^2, indicating the significant ($P \leq 0.05$) effect of EM. In comparison with the previous low level (100 with 0 L EM ton^{-1} of OM and so on), the 100 L ton^{-1} made a considerable increase in leaf area $tiller^{-1}$ (6.3 cm^2) compared with 200 (5.1 cm^2) and 300 L EM ton^{-1} of OM (3.7 cm^2). The OM × EM interaction across average over-year data (Figure 3c) showed an increase in leaf area $tiller^{-1}$ at increasing levels of EM from 0 to 300 L EM ton^{-1} of OM across PM, FYM, and MR treatments. However, in the compost treatment, the leaf area $tiller^{-1}$ exhibited an increase as levels of EM from 0 to 200 L ton^{-1} of OM increased. Afterward, a significant decrease showed with a further buildup of EM to the highest level (300 L ton^{-1} of OM). However, in the control treatment, the leaf area $tiller^{-1}$ was at a relatively comparable level across all levels of EM.

The plant height showed non-significant variations between 2017–2018 and 2018–2019 (Table 2). During 2017–2018, the OM and EM brought about significant variations in plant height. The PM increased the plant height by 2.7 and 9.8 cm compared with the FYM and control, respectively. Similarly, using compost and MR, the average increase in plant height was 3.9 cm than the control. The different levels of EM (100, 200, and 300 L ton^{-1} of OM) remained at a comparable level with each other in terms of plant height but were significantly higher than the control. In 2018–2019, the plant height recorded with PM (94.4 cm) was significantly higher than the control (84.5 cm) but comparable with the FYM treatment (93.3 cm). Likewise, using 100 L EM ton^{-1} of OM, a slight increase (1.9 cm) occurs in plant height compared with 0 L EM ton^{-1} of OM. However, adding 200 and 300 L EM ton^{-1} of OM significantly increases the plant height (3.9 and 4.3 cm) compared with 0 L EM ton^{-1} of OM. The OM × EM interaction (Figure 3d) plotted against the first-year data showed a linear response of plant height with increasing levels of EM from 0 to 300 L ton^{-1} of OM across PM and FYM treatments. Conversely, in compost, the plant height initially increased with EM in the range of 0 to 100 L ton^{-1}, then significantly decreased with a further addition of EM from 100 to 300 L ton^{-1} of OM. In the case of MR and control, no significant changes in plant height showed with increasing levels of EM.

Dry matter accumulation and crop growth rate

Dry matter accumulation was influenced by OM (Figure 4a) and EM (Figure 4b) during both years, specifically beyond 40 days after sowing. However, OM × EM interaction showed non-significant for DM accumulation at 80, 140, and 160 days after sowing. The PM brought about significant increases in DM accumulation over other sources of OM. The increase in DM accumulation over control (average over intervals) was 28.2%, 24.2%, 17.4%, and 16.4% with PM, FYM, MR, and compost, respectively. Likewise, 300 L EM ton^{-1} of OM resulted in higher DM accumulation than lower levels. Yet, no significant differences in DM accumulation occurred with 200 and 300 L ton^{-1} at most of the sampling intervals from 20 to 120 days after sowing. In general, the DM accumulation was slow during the early stages of wheat growth till 40 days after sowing but rapidly increased till maturity. Still, the accumulation of DM was more pronounced from 100 to 120 days after sowing compared with other intervals. Significant variations in CGR appeared under the influence of OM and EM across all sampling intervals, except 160 days after sowing, where the EM was found non-significant. The CGR progressively increased after sowing until peaking at 100–120 DAS across all the PM and application of 300 L EM ton^{-1} of OM. At such intervals, the CGR observed with FYM and PM was statistically comparable but higher than the compost and control (Figure 5a). Likewise, the CGR was 7%, 5.3%, and 2.9% higher with 300, 200, and 100 L ton^{-1} compared with 0 L EM ton^{-1} of OM (Figure 5b).

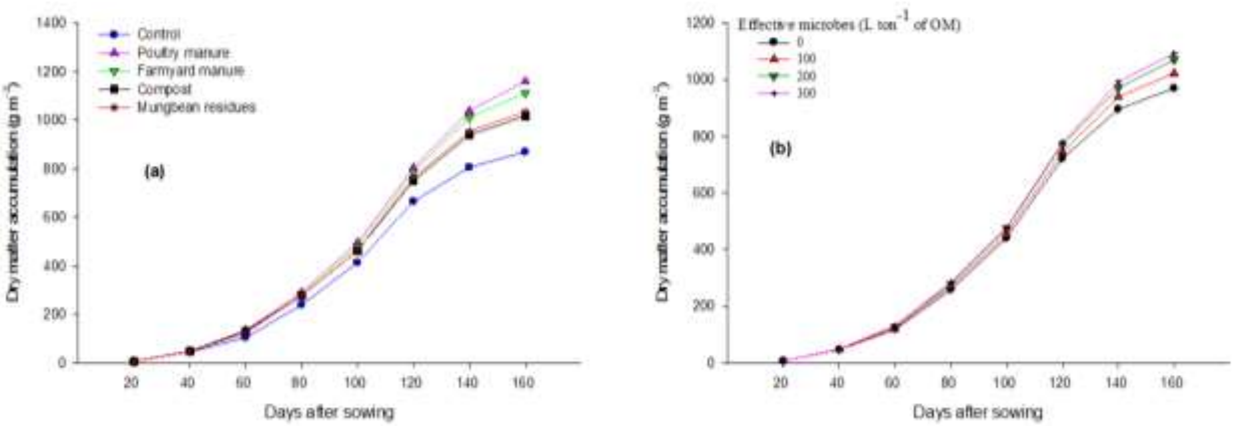

Figure 4. Dry matter accumulation (g m^{-2}) after sowing of wheat in response to sources of organic matter (a) and levels of effective microbes (b).

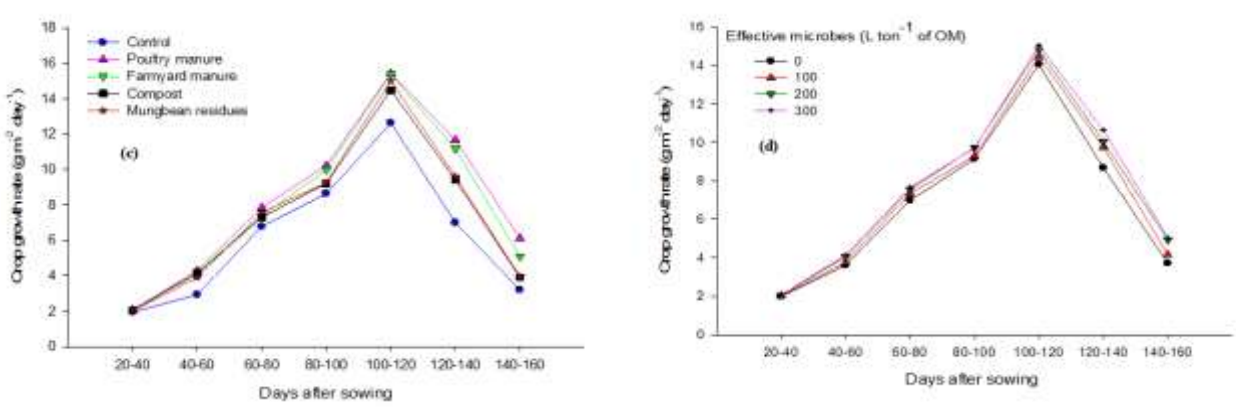

Figure 5. Crop growth rate (g m^{-2} day^{-1}) after sowing of wheat in response to sources of organic matter (a) and levels of effective microbes (b).

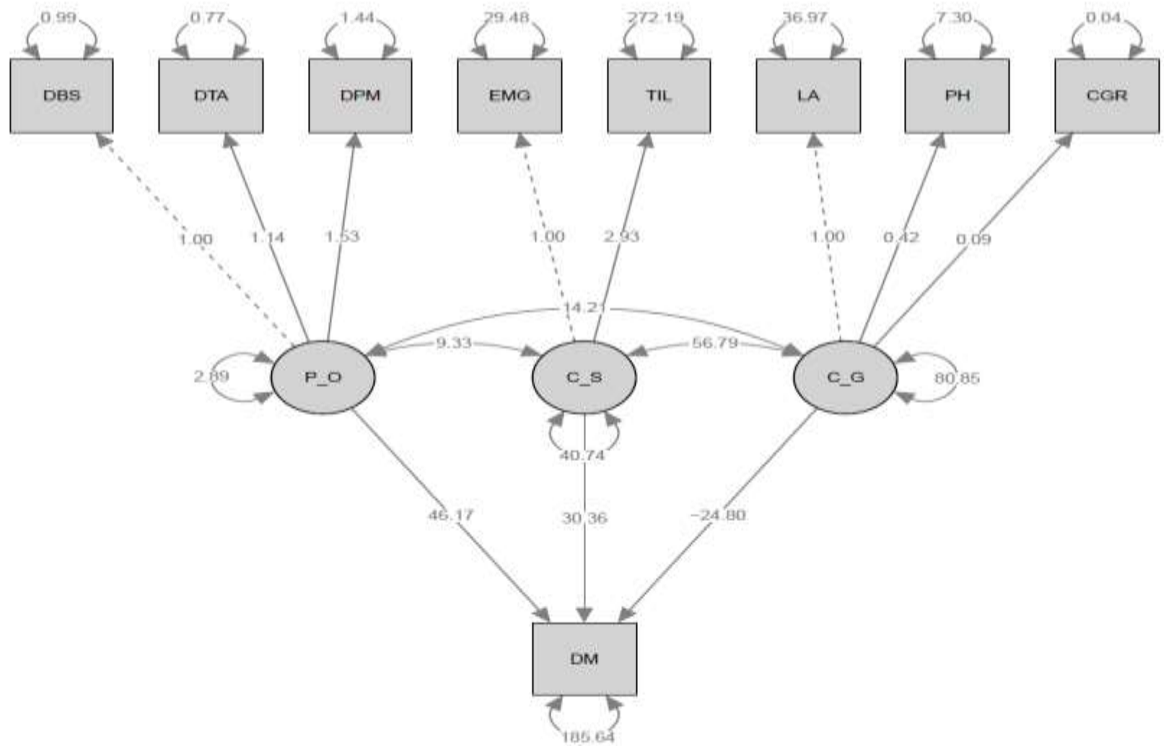

Figure 6. Relationship of dry matter (DM) with crop phenological observation (P_O), i.e., days to boot stage (DBS), days to anthesis (DTA), days to physiological maturity (DPM); crop stand (C_S), i.e., emergence m^{-2} (EMG) and tiller m^{-2} (TILL); crop growth (C_G), i.e., leaf area (LA), plant height (PH), and crop growth rate (CGR) as per Structural Equation model. $\chi 2$ = 0.272; CFI = 0.996; GFI = 0.911; and RMSEA = 0.045. The numbers on the arrows represent the standardized path coefficients. The bold and dashed arrows indicate positive and negative significant paths, respectively.

Structural Equation model

The dependency and relationship of dry matter production of wheat to crop phenological observation (P_O), i.e., days to boot stage (DBS), days to anthesis (DTA), days to physiological maturity (DPM), crop stand (C_S), i.e., emergence m^{-2} (EMG) and tiller m^{-2} (TILL), crop growth (C_G), i.e., leaf area (LA), plant height (PH), and crop growth rate (CGR) underwent further analysis by the structural equation modeling (Figure 6). The model explained 46.16%, 30.36%, and 24.80% of the variations caused due to P_O, C_S (directly), and C_G (indirectly), respectively. Specifically, the P_O and C_S directly and positively influenced the dry matter accumulation in wheat, whereas the C_G negatively affected the dry matter accumulation in wheat.

DISCUSSION

The incorporation of PM, FYM, and compost resulted in higher emergence and tiller m^{-2} of wheat than MR and control. Emergence is a yield-contributing factor, as it determines crop stand establishment and the productive potential of plants. The crop management practices like soil moisture, soil pH, and temperature (Humphries *et al.,* 2018) strongly affect the emergence of a crop. Manures regulate soil temperature and make the soil permeable, which might have encouraged the imbibition of water and release of substrates necessary for crop germination (Bhavin and Kapoor, 2019), resultantly improved crop stand. The optimum N availability promotes the plant's physiological processes and meristematic activities and boosts the formation of new tillers primordia (Rasul *et al.,* 2015), thereby improving the crop stand. The mungbean residues mixed with soil might result in a less consolidated seedbed and impede the seedling emergence (Greff *et al.,* 2022). However, during the second year, the higher emergence at MR over control might be accredited to favorable soil conditions like soil porosity and soil enzymatic activities due to repeated application of MR.

The addition of EM did not significantly affect the emergence and tillers m^{-2}, which might be associated with the role of stored endospermic food of the seed in germination. But, the repeated application of microbes during the second year enhanced the tillering over control irrespective of its levels. The possible mechanism for higher tillering may result from transforming organic N to available N (Rasul *et al.,* 2015; Chen *et al.,* 2018) and intense microbial activities (Naik *et al.,* 2019). These findings gained support from Anjum and Khan (2021), who reported higher decomposition and release of nutrients with the addition of EM. Adnan *et al.* (2022) also observed a higher tillering capacity of wheat by adding microbes with manures.

Delayed booting, anthesis, and maturity came about with the addition of PM compared with other sources during both years. Better mineralization with PM over other sources might enhance nutrient availability, especially nitrogen (Rasul *et al.,* 2015; Adnan *et al.,* 2022), which might result in vigorous growth (Anjum and Khan, 2020). Nitrogen, as the structural and functional component of a plant's cell, might improve the chlorophyll contents and vegetative plant vegetative, hence delaying the phenology. Moreover, the MR and compost took similar days to boot and anthesis during the first year. However, during the second year, the MR delayed the booting and anthesis over the compost. The lower decomposition of MR during the early period of incorporation compared with later stages caused early phenology due to a limited supply of nitrogen (Ali *et al.,* 2015; Rena *et al.,* 2019). But the optimum mineralization during the second year, as a result of repeated application, enhanced the crop growth (Anjum and Khan, 2021) and nutrient availability, thus, delaying booting and anthesis. Furthermore, the limited progress due to nutrient-deficient conditions across control might create stress and, therefore, get early booting and anthesis compared with OM incorporation (Ali *et al.,* 2015).

The higher levels of EM delayed the booting and anthesis by two days compared with the control (0 L ton^{-1} of OM), as shown by the average over the year's data. Days to booting and anthesis were not affected by the application of EM above 200 L ton^{-1} across both years, except days to booting during the first year, where 300 L EM ton^{-1} of OM delayed the booting by one day over 200 L EM ton^{-1} of OM. Greater mineralization with higher levels of EM might be the possible reason for delayed booting and anthesis (Khan *et al.,* 2019). These findings agreed with Anjum and Khan (2020), who reported delayed phenology by adding EM compared with other amendments.

Plant height is an essential component of plant biomass. It is a genetically controlled character but also has inclinations with climatic (moisture, temperature, and light), edaphic (soil permeability, soil temperature, nutrients, and organic matter), and management practices (Liu *et al.,* 2018). Taller plants with PM are attributable to improved soil fertility, nutrient provision due to higher microbial activities, and optimum root growth and development (Khan *et al.,* 2015). The immense release of N by PM could be another reason for improved plant height, as it is a component of growth-promoting enzymes, proteins, and chlorophyll (Akhtar *et al.,* 2018; Akhtar *et al.,* 2019b). The higher N availability could enhance the cell enlargement, increasing internode length and plant height (Rena *et al.,* 2019).

The incorporation of EM had increased the plant height over control (0 L ton^{-1} of OM). The taller plants observed using EM may have resulted in more nutrients (NPK) availability from OM (Joshi *et al.,* 2019; Naik *et al.,* 2019) or a better rooting system owing to microbial activities (Khan *et al.,* 2015; Joshi *et al.,* 2019). The other possible mechanism for improved plant height might be the active cell division and enlargement resulting from bioactive substances released by EM in the rhizosphere (Talaat *et al.,* 2015; Adnan *et al.,* 2022). These results follow the findings of Iriti *et al*. (2019), who reported higher shoot growth by adding EM compared with the control.

The increased leaf area with PM during the first year and PM/FYM during the second year over other sources of OM may refer to the effectiveness of this manure in improving crop growth rate and dry matter accumulation. The possible reasons for this phenomenon might be the improved soil physical and chemical properties (Muhammad *et al.,* 2018), microbial activities (Anjum and Khan, 2021), and the transformation of nutrients (Khan *et al.*, 2019) ensuring a prolonged supply of plant essential nutrients (Ali *et al.*, 2015) and, consequently, improving the plant growth (Akhtar *et al.,* 2019b). The balance availability of nutrients enhanced the leaf area, which increased the photosynthetic activity, cell division, and plants' physiological processes (Akhtar *et al.,* 2019b) and, hence, more CGR and dry matter accumulation. The other possible mechanism for improved leaf area can refer to enhanced mineralization, which increases N availability and plant height and, eventually, enhances the number of leaves and their expansion (Khan *et al.,* 2015). The DM accumulation increased beyond 40 DAS and reached its maximum values at physiological maturity. This increase can be due to forming of new tillers and leaf areas. The higher DM production with poultry manure could be accredited to enhanced mineralization and release of nutrients during the early stages of incorporation (Wang *et al.,* 2020). An observation also revealed that CGR attained peak values at 120 DAS and then dropped irrespective of the treatment used. The reduction in LAI beyond anthesis and leaf senescence (Ihsan *et al.,* 2016) might be the probable reason for the decline in CGR beyond 120 DAS.

Adding effective microbes improved the leaf area, CGR, and dry matter accumulation. The leaf area tiller^{-1} was bigger with higher levels (200 and 300 L ton^{-1} of OM) compared with lower levels (0 and 100 L ton^{-1} of OM) of EM. The higher levels of EM increased the mineralization of OM (Anjum and Khan, 2021) and the synthesis of amino acids and protein (Iriti *et al.,* 2019), which in turn increased the crop growth and leaf area (Talaat *et al.,* 2015). The release of phytohormones and growth regulators by EM makes the soil environment favorable for root growth, improving nutrients' uptake (Chen *et al.,* 2018; Yadav *et al.,* 2022), which in turn increasing the net photosynthesis and leaf expansion (Iriti *et al.,* 2019), assimilating formation (Akhtar *et al.,* 2019b) and, consequently, increasing the aboveground biomass production.

The structural equation models further authenticated the improvement of dry matter by balanced nutrient availability in PM/FYM with 300 L EM ton^{-1}. Overall, in the structural equation model, crop phenology and stand had a direct positive effect, whereas crop growth had adverse and indirect effects on the dry matter production in wheat. The presence of a direct causal relationship between crop phenology and crop stand on dry matter production of wheat in the structural equation model suggests superior influences on crop stand and phenological observation in terms of dry matter production as compared with crop growth parameters. Thus, crop supplements like added manure/residues, if mixed with effective microbes and increased nutrient availability, are likely the prime cause of various dry matter production under PM-treated plots compared with the control.

CONCLUSIONS

Organic matter sources (OM) and effective microbes (EM) had significantly altered wheat phenological stages, growth, and dry matter (DM) production. The poultry manure (PM) has delayed phenology and improved the leaf area (30%), DM (28.2%), and CGR (33.6%) over the control, suggesting the sufficiency of PM for obtaining enhanced production. The higher level of EM at 300 L ton^{-1} of OM had increased the tillers m^{-2} (10.9%), leaf area (11%), DM (10.2%), and CGR (7%) over 0 L of EM. The improvement of dry matter via balanced nutrient availability using PM/FYM with 300 L EM ton^{-1} of OM gained authentication by structural equation models. The maximum DM (55%) accumulated in plant parts was beyond 100 days after sowing (DAS), with marked increases at 60 DAS and decreasing CGR beyond 120 DAS. The compost performed well at lower levels of EM (200 L ton^{-1}), whereas PM, FYM, and MR at a higher level (300 L ton^{-1} of OM) of wheat growth and DM production. The long-term study on organic amendments would demonstrate the potential changes in soil fertility and sustainable crop productivity.

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