WHEAT GROWTH AND SUBSEQUENT MAIZE PRODUCTIVITY INTERACTION WITH AM FUNGI UNDER REDUCED PHOSPHORUS APPLICATION FROM ORGANIC AND INORGANIC SOURCES IN CALCAREOUS SOIL

Mehran Ali[1*] and Inamullah[1]

1. Department of Agronomy, The University of Agriculture Peshawar, Pakistan

**Corresponding author*

Abstract

Inoculation of arbuscular mycorrhizal (AM) fungi could be helpful in the sustainable management of immobile P in soil. However, their use in releasing P from alternative sources in alkaline calcareous soils has been little investigated. To explore the influence of AM fungi and P management on wheat and subsequent maize productivity, two years of field experiments were carried out at Agronomy Research Farm, The University of Agriculture Peshawar, during the Rabi season 2018-19 and 2019-20. A randomized complete block design was used to test the efficacy of different P sources {1. Single super phosphate (SSP), 2. Rock phosphate (RP), 3. Poultry manure (PM), 4. 50% SSP + 50% PM and 5. 50% RP + 50% PM} applied at the rate of 60 and 90 kg P ha^{-1}. These treatments were explored with and without the incorporation of AM fungi. One control treatment was used for reference. The results exhibited that AM fungi had a non-significant effect on the initial phenological stages of wheat, like days to emergence, tillering, and anthesis, but considerable variations were recorded for physiological maturity as well as physiology and yield of both wheat and succeeding maize. Different P levels also revealed a similar trend, 90 kg P ha^{-1} noted better phenology, physiology, and yield of wheat and maize, however, keeping monetary and sustainability in consideration, reduced P level (60 kg ha^{-1}) was more convincing when explored under AM fungi application. Regarding P sources, the co-application of SSP and PM in a 50:50 ratio performed comparatively better than the rest of the sources under consideration in field trials. Conclusively, the combined application of SSP and PM at the rate of 60 kg $ha^{-1,}$ along with AM fungi incorporation, provides an edge over the conventional use of synthetic P fertilizer. Moreover, AM fungi provide improved infrastructure to transfer P to plants for growth promotion

under reduced P levels, and it has more potential to improve wheat yields and P uptake on a sustainable basis in P-deficient calcareous soils.

Keywords: AM Fungi, P management, Wheat, Maize, Productivity

Introduction

Wheat (*Triticum aestivum* L.) accounts for the largest source of vegetable protein in human food as well as it fulfills about half of the carbohydrates and one-fifth of the global food calories requirement (FAOSTAT, 2020). In Pakistan, it provides nearly 30% of the total food grain basket, particularly under cereal-based cropping patterns (MNFSR, 2019). Maize (*Zea mays* L.) is the vital cereal crop of Pakistan after wheat and rice and generally used as a source of food and feed. Regardless of immense potential, the national average productivity of wheat is 2769 kg ha^{-1} and , much lesser than the yield obtained in developed states (MNFSR, 2019). Despite higher investment and inputs, wheat and maize productivity in Pakistan is undergoing stagnation and even follows a declining trend in some areas. The declining crop and soil productivity trend may be attributed to the adoption of conventional practices, imbalance use of fertilizers, and no inclusion of beneficial soil biota.

Soil microorganisms, particularly AM fungi, had a significant role in the wheat-maize cropping system by affecting the efficacy of applied fertilizers and residual influence (Hussain *et al.*, 2016; Jan *et al.*, 2014). Symbiotic associations were made between plants and AM fungi, where up to 90% P and 20% Nitrogen (N) of plants supplied from AM fungi with soil hyphal networks in response to plant photosynthates (Bakhshandeh *et al.*, 2017). Besides accessibility, AM fungi increased nutrient interception through hyphae, possibly reducing nutrient loss from the rhizosphere (Cavagnaro *et al.*, 2015). Under relatively meager nutrient conditions, such associations of symbiosis have played a pivotal role. For instance, lower availability of soil P could stimulate AM fungi colonization, which ultimately enhances P, N, and Zn utilization and avert its losses (Behlr *et al.*, 2015).

P is one of the macro and most essential plant nutrients required by crops in large amounts to ensure higher yield (Imran *et al.*, 2014) and soil productivity (Inamullah and Khan, 2015). P has the mayhem of immobility in the soil, and despite of higher level of application, only a part of it is available for plant uptake. According to Manimaran (2014), the contribution of phosphorus to biomass production cannot be overlooked due to its involvement in many biochemical and physiological processes in the plant's body. Pakistani soils are widely P deficient, so their adequate application is indispensable for optimum yield and quality of crops (Aslam, 2016). The ever-escalating prices of commercial P fertilizers throughout the country engendering the need to discover some substitute sources and methodology. So, it could relieve small-scale farmers by lowering production costs and improving the utilization efficiency of applied fertilizers.

For sustainable P management and crop productivity using the available resources, the better option could be the co-application of inorganic and organic P sources (Ali *et al.*, 2020). Coupling of both organic-inorganic sources may not only improve the crop yield and soil fertility (Sharif *et al.*, 2012) but also the farmer's net return (Ali *et al.*, 2019) because it improves the efficiency of applied fertilizers (Uwah *et al.*, 2011) and reduce the fertilizers losses (Zafar *et al.*, 2017). Wahid *et al.* (2016) reported a 25% higher economic yield with rock phosphate and poultry manure applied in a 50:50 ratio. Furthermore, Shahzad *et al.* (2015) documented a considerable increase in maize yield and yield-related parameters (cob weight, cob length, 100-grains weight, shelling percentage, etc.) from their multi-year experiments through the application of PM plus phosphatic mineral fertilizers.

Thus, considering the significance of AM fungi and the co-application of organic-inorganic P fertilizers, the current research study was designed to study the role of AMF and P fertilizers for getting higher productivity and optimization of wheat growth and subsequent maize productivity in the cereal-based cropping system.

Materials and Methods

AM Fungi

AM Fungi spores were isolated using the Wet-sieving and decanting technique (Wahid *et al.*, 2016). This indigenous AMF inoculum was dominated by *Glomus intraradices,* whereas the spores of *Glomus fasiculatum* and *Glomus mossea* were in minor quantities. For this purpose, 20 g alkaline calcareous soil samples were taken from the field cultivated with spring maize, having silty clay loam rhizosphere. The AMF spores were observed in the soil samples through a binocular microscope having 40X magnification power. For each pot, 100 spores were isolated and stored in Petri plates as a suspension at 4°C for about 48 hours before application. The suspension was then applied to pots along with sorghum (*Sorghum bicolor*) seeds to raise optimum inoculum for the application of extensive field trials. The plant roots with rhizosphere soil were applied at the rate of 1 kg m^{-2}.

Experimental site

A series of field trials were conducted at Agronomy Research Farm, The University of Agriculture Peshawar, during Rabi Season 2018-19 and 2019-20. The field trial site has a continental climate located at 71.46^0 E, 34.02^0 N, and 359-meter altitude above sea level. The physicochemical properties of the site are given in Table 1.

Table 1. Physico-chemical properties of the experimental site and PM.

Characteristics	Soil	PM
Sand (%)	7.81	--
Silt (%)	39.4	--
Clay (%)	52.7	--
Textural class	Silty clay loam	
$pH_{1:5}$ (H_2O)$^+$	8.02	7.82
$EC_{1:5}$ (dSm^{-1})$^+$	0.18	1.34
BD (g cm^{-3})	1.25	--
Organic matter (%)	0.84	--
Total Nitrogen (%)	0.051	1.83
Mineral Nitrogen (mg kg^{-1})	19.13	--
Organic carbon (g kg^{-1})	5.73	674
AB-DTPA extractable P (mg kg^{-1})	2.84	25.6
AB-DTPA extractable K (mg kg^{-1})	81.1	--
Calcium carbonate (%)	17.0	--

+ = pH and EC of PM was measured on 1:10 (w/v basis)

Experimental treatments and design

Randomized Complete Block design was used to test the efficacy of different P sources {1. Single super phosphate (SSP), 2. Rock phosphate (RP), 3. Poultry manure (PM), 4. 50% SSP + 50% PM and 5. 50% RP + 50% PM} applied at the rate of 60 and 90 kg ha^{-1}. These treatments were explored with and without the incorporation of AM fungi. One control treatment was used for reference, and the experiment was replicated four times. Test variety KHAISTA-2017 was planted in a 3m x 3m plot size. Each experimental unit consisted of ten rows (3m length) with 0.3m row to row distance. All the P sources were incorporated at the time of sowing along with potash application at the rate of 60 kg ha^{-1} uniformly. However, half of the nitrogen (75 kg) was applied at sowing, and the remaining half was at tillering stage. Recommended irrigation schedules and other agronomic practices were kept uniform for all the experimental units. The experimental trial was harvested when the crop reached harvest maturity, i.e. 30-34% grain moisture contents, on 11th May 2020 and 13th May 2021.

Measurements and observations

Germination m^{-2} was considered when 85% of seedlings emerged in each experimental unit. Phenological stages were quantified by days' difference between planting to date when about 75% of plants in each sub-plots reached anthesis and physiological maturity. Similarly, physiological maturity was taken when 70% of the physical structure of the crop stand appeared yellowish-brown. The leaf area index (LAI) was calculated as the ratio of plants' total leaf area (LA) and the total ground area covered by the plants. SPAD value was taken on five flag leaves randomly selected in each plot with SPAD meter to approximate the leaf chlorophyll content. For grain yield, four central rows of wheat and two of maize crop in each plot were harvested, sundried for a couple of days, then threshed/shelled, weighed, and finally converted to kg ha^{-1} using the formula:

$$\text{Grain yield (kg ha}^{-1}) = \frac{\text{Grain yield of four/two central rows}}{\text{R} - \text{R distance(m)} \times \text{Row length(m)} \times \text{no. of rows}} \times 10{,}000\text{m}^2$$

The data was statistically analyzed using the appropriate ANOVA for Randomized Complete block design and LSD at 0.05 level of probability (Jan *et al*., 2009).

Results

1. Crop phenology

i. Days to emergence and germination m^{-2}

Data regarding days to emergence and germination m^{-2} of wheat as affected by AMF application, P levels and P sources are presented in Table 02. Analysis of the data showed that AMF, P levels, and sources had non-significant effects on days taken to emergence and germination counted per unit area. Similarly, the planned mean comparison of control against rest had no significant impact on wheat seed emergence interval, and seedlings emerged in a unit area. Correspondingly, all the possible interactions were also found non-significant.

ii. Days to Anthesis

P sources had significant, while AMF and P levels had non-significant effects on days to anthesis of wheat (Table 02). All the interactions between AMF, P levels, and sources were non-significant. The mean values of the data indicated delayed anthesis with the application of PM (123 days), followed by RP and RP+PM incorporation. Early anthesis (121 days) was observed in plots where the P source was applied from SSP. Control plots, in comparison with fertilized plots, took more (124 days) to anthesis.

Table 02. Phenological events and germination (m^{-2}) of wheat as affected AMF and P management

Arbuscular Mycorrhizal Fungi (AMF)	Days to emergence	Germination (m^{-2})	Days to anthesis	Days to physiological maturity
+AMF	14±0.01	120±0.3	122±2.1	157±1.8 b
-AMF	14±0.30	120±0.9	122±2.2	158±1.7 a
LSD (P<0.05)	NS	NS	NS	0.42
Phosphorus Levels (PL)				
60 kg ha^{-1}	14±0.19	118±0.4	122±2.0	158±1.9 a
90 kg ha^{-1}	14±0.12	122±1.0	122±2.2	157±1.7 b
LSD (P<0.05)	NS	NS	NS	0.44
Phosphorus Sources (PS)				
Single Super Phosphate (SSP)	14±0.04	119±0.7	121±2.5 c	157±1.9 c
Rock Phosphate (RP)	14±0.31	117±1.1	122±2.3 b	158±1.6 b
Poultry Manure (PM)	13±0.17	123±1.3	123±1.7 a	159±1.5 a
SSP + PM (50:50)	14±0.39	123±2.2	122±2.1 b	159±1.8 a
RP + PM (50:50)	14±0.27	119±3.2	122±2.2 b	158±2.1 b
LSD (P<0.05)	NS	NS	0.57	0.69

Means followed by different letters within a category of a treatment are statistically different from each other using LSD test (p<0.05). Means were followed by ± Standard deviation between means over years

iii. Days to Physiological Maturity

Perusal of the data presented in Table 02 revealed that AMF, P levels, and sources significantly affected the days taken to the physiological maturity of wheat. The planned mean comparison of control vs. rest was also found significant. However, all the possible interactions were found non-significant. Plots incorporated with AMF inoculum noted early physiological maturity (157 days) than no-AMF applied units. Comparing different rates of P, delayed physiological maturity (158 days) noted in P applied at the rate of 60 kg ha^{-1}. Whereas 90 kg P ha^{-1} applied plots took fewer days to physiological maturity. Mean values of the different P sources indicated delayed physiological maturity with the application of PM (159 days), followed by RP and RP+PM incorporated experimental units. Early physiological maturity (157 days) was observed in plots where SSP was incorporated as a P source. Control plots, in comparison with fertilized plots, took more days (160) to physiological maturity.

2. Crop physiology

i. SPAD Value

Data pertaining to the SPAD value of wheat as affected by AMF, P levels, and P sources are given in Table 03. Statistical analysis of data revealed that the SPAD value of wheat differed significantly in response to AMF and different P sources. However, P levels and all the possible interactions were insignificant except AMF x PS. The mean values of AMF application revealed a higher SPAD value (55.0) with the incorporation of mycorrhiza inoculum. Regarding different P sources, the co-application of SSP and PM in the 50:50 ratio noted a higher SPAD value (55.8) which was statistically similar to PM (54.2) and SSP. Plots fertilized with RP as a P source observed a lower SPAD value (53.0) of wheat. In AMF x PS, P applied in both sole and integrated form resulted in a positive increase in wheat SPAD value when AMF was amended. However, an exception exists in the case of the SSP application, where no considerable increase was recorded in SPAD value with AMF (Fig. 01).

ii. Leaf Area Index (LAI)

Data regarding LAI of wheat as affected by AMF, P levels, and P sources are given in Table 03. Statistical analysis of data revealed that the LAI of wheat differed significantly in response to the application of AMF, P levels, and different P sources. However, all the possible interactions were insignificant except PL x PS, AMF x PL, and AMF x PS. Mean values of data regarding AMF indicated higher LAI (3.84) in AMF-amended plots than in no-AMF applied plots (3.41). Likewise, P application at the rate of 90 kg P ha^{-1} produced higher LAI (3.69) as compared with 60 kg P ha^{-1} (3.55). Regarding different P sources, the addition of integrated P sources (50%SSP+50%PM) produced a higher LAI (4.02), which was followed by SSP-amended units with LAI of 3.67. Plots fertilized with RP produced lower LAI of wheat (3.34). Considering the PL x PS interaction effect, a significant positive increase was observed in LAI when various P sources were applied at a higher rate than the reduced one. At 60 kg P ha$^{-1,}$ the SSP+PM application showed a promising increase compared to the other sources. However, at 90 kg P ha^{-1} highest LAI was observed in sole SSP-incorporated plots (Fig. 02). The interaction of AMF x PL revealed that AMF incorporation had a positive effect on LAI under both levels. However, the effect was more prominent with reduced P application (Fig. 03). In AMF x PS, P applied in the form of both sole and integrated responded positively when AMF was amended. However, an exception exists in the case of the SSP application, where no considerable increase was recorded in LAI with AMF incorporation (Fig.04).

Table 03. SPAD value, LAI, and grain yield (kg ha^{-1}) of wheat and subsequent maize as affected AMF and P management

Arbuscular Mycorrhizal Fungi (AMF)	Physiology		Grain yield (kg ha^{-1})	
	SPAD Value	LAI	Wheat	Maize
+AMF	55±1.5 a	3.84±0.00 a	3875±137 a	3669±122 a
-AMF	53±2.8 b	3.41±0.04 b	3683±124 b	3332±221 b
LSD (P<0.05)	0.52	0.07	59.4	68.2
Phosphorus Levels (PL)				
60 kg ha^{-1}	54±2.1	3.55±0.03 b	3630±128 b	3471±298
90 kg ha^{-1}	54±2.1	3.69±0.02 a	3927±133 b	3530±45
LSD (P<0.05)	NS	0.08	62.3	NS
Phosphorus Sources (PS)				
Single Super Phosphate (SSP)	54±2.3 b	3.67±0.03 b	3808±114 b	3588±70 a
Rock Phosphate (RP)	53±2.3 c	3.34±0.05 c	3616±149 c	3237±191 c
Poultry Manure (PM)	54±2.1 b	3.66±0.03 b	3743±105 b	3429±209 b
SSP + PM (50:50)	56±1.9 a	4.02±0.02 a	3968±139 a	3664±210 a
RP + PM (50:50)	54±2.0 b	3.42±0.04 c	3763±145 b	3585±178 a
LSD (P<0.05)	0.87	0.13	98.5	113.2

Means followed by different letters within a category of treatment are statistically different from each other using the LSD test (p<0.05). Means were followed by ± Standard deviation between means over years

3. Wheat grain yield (kg ha^{-1})

Analysis of variance showed a significant effect of AMF, P levels, and various P sources on the grain yield of wheat (Table 3). However, all the possible interactions except PL x PS and AMF x PS were found non-significant for the grain yield of wheat. Considering AMF application, plots incorporated with AMF produced higher grain yield (3875 kg ha^{-1}) as compared with no AMF applied plots (3683 kg ha^{-1}). Likewise, P levels also varied the grain yield. Application of 90 kg P ha^{-1} produced higher grain yield (3928 kg ha^{-1}) than reduced P application i.e. 60 kg ha^{-1}. Among various P sources, addition of P from SSP+PM produced higher grain yield (3968 kg ha^{-1}) which was followed by SSP. Application of RP as a P source had a lower grain yield (3616 kg ha^{-1}). The interactive response of PL x PS revealed an increasing trend in grain yield when the rate of P applied changed from 60 to 90 kg P ha^{-1} irrespective of the sources (Fig. 05). In a similar way, different P sources incorporated in combination with AMF, performed significantly better when compared with sole application of them (Fig. 06).

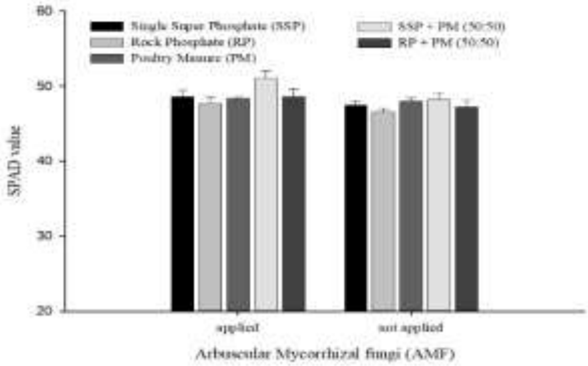

Fig. 01. Interaction between AMF and P sources for SPAD value of wheat

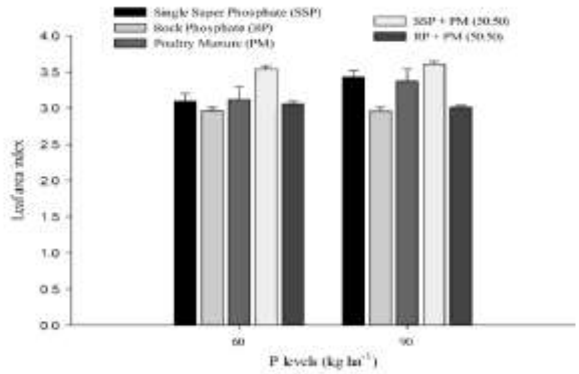

Fig. 02. Interaction between P levels and P sources for LAI of wheat

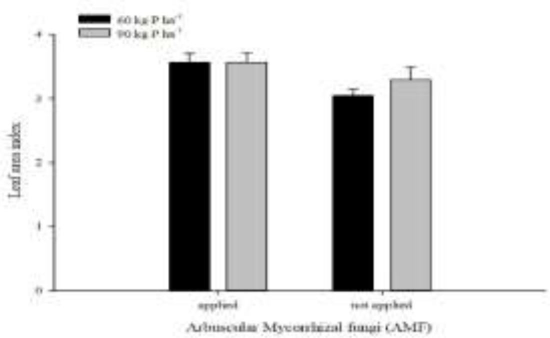

Fig. 03. Interaction between AMF and P levels for LAI of wheat

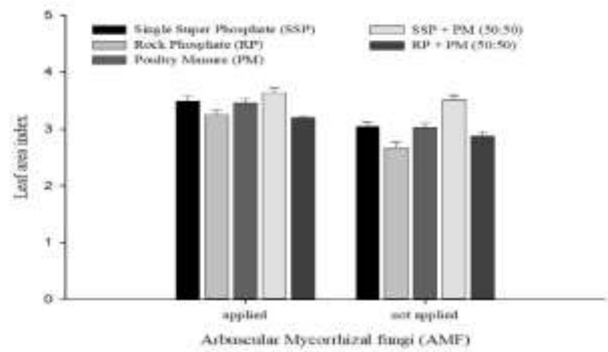

Fig. 04. Interaction between AMF and P sources for LAI of wheat

4. Subsequent maize yield (kg ha^{-1})

Data pertaining to grain yield (kg ha^{-1}) of subsequent maize as affected by the residual effect of AMF, P levels, and P sources are given in Table 03. Statistical analysis of data revealed that grain yield of subsequent maize differed significantly in response to the residual effect of AMF application, P levels, and different P sources. However, all the possible interactions were not significant except AMF x PS and Y x PL. Mean values of AMF application revealed that maize grain yield (3669 kg ha^{-1}) was higher with the incorporation of mycorrhiza inoculum into the previous wheat crop. Regarding different PS, the preceding co-application of SSP and PM in the 50:50 ratio produced higher maize grain yield (3664 kg ha^{-1}) which was statistically at far with 100% SSP as well as 50%SSP+50%RP. RP-amended plots produced a lower subsequent maize grain yield (3237 kg ha^{-1}). The interaction of AMF x PS showed that AMF amended plots reported higher maize grain yield irrespective of the P sources applied to the preceding crop. However, different P sources responded differently under AMF, like SSP applied plots observed a smaller change in maize grain yield when compared to the rest. Conversely, 100%PM, 100%RP, and 50%SSP+50%PM noted significant positive changes in the maize grain yield along with AMF application (Fig. 07).

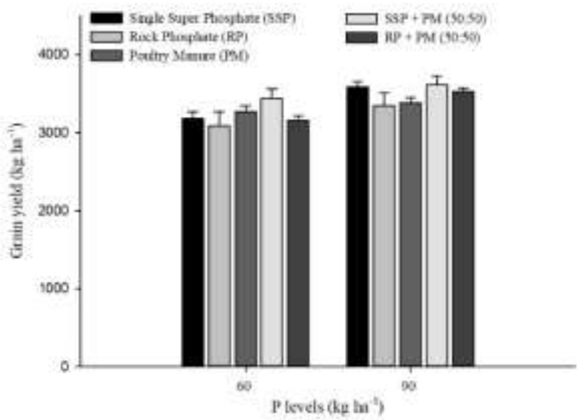

Fig. 05. Interaction between P levels and P sources for grain yield (kg ha^{-1}) of wheat

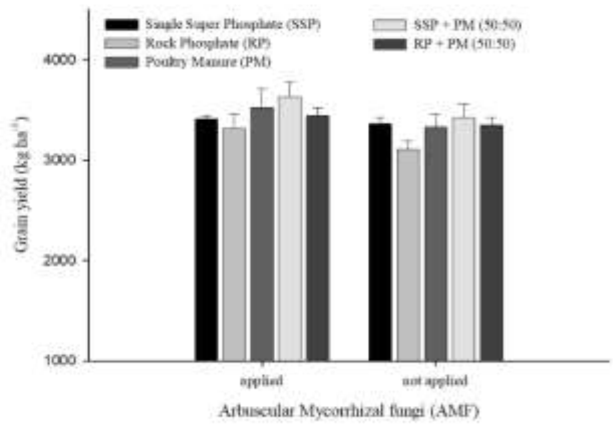

Fig. 06. Interaction between AMF and P sources for grain yield (kg ha^{-1}) of wheat

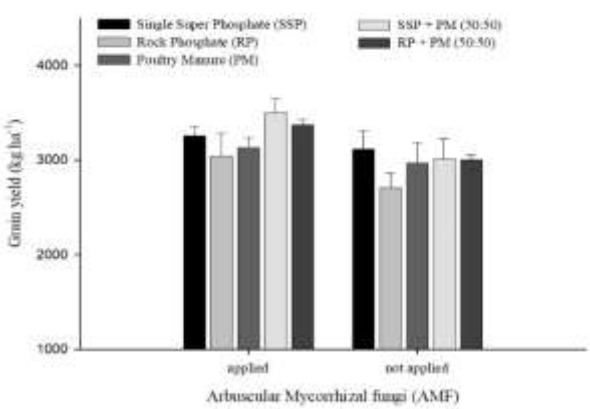

Fig. 07. Interaction between AMF and P sources for subsequent maize grain yield (kg ha^{-1})

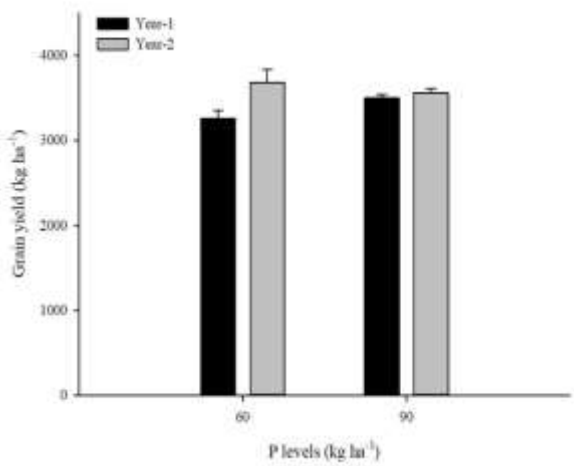

Fig. 08. Interaction between Year and P levels for subsequent maize grain yield (kg ha^{-1})

Discussion

AMF incorporation had a non-significant effect on earlier events and negatively affected the later phonological observations. The possible reason for the altering crop phenology is P uptake through the diffusion process coupled with increasing root exploration with indigenous AMF addition (Campos *et al.*, 2018). Higher P uptake encourages the reduction of the vegetative period and accompanies the transition to reproductive growth (Ortas and Bykova, 2018). Limiting P acquisition supports delaying the transformation to the reproductive stage and might be disproportionately beneficial for P acquirement (Yousefi *et al.*, 2011). Similar results were also observed by Pellegrino et al. (2015), who documented that wheat growth and phonological observation, like days to anthesis and physiological maturity, were optimized with AMF inoculation.

Initial stages like days to emergence and emergence m^{-2} had no considerable variation with applied P irrespective of levels and sources. The emergence of seed mostly depends on above (air temperature) and below (soil temperature) (Saharan et al., 2016), food stored inside cotyledon (Saikia *et al.*, 2015), and the presence of available moisture (Zavattaro *et al.*, 2017). These results corroborate with Khalil *et al.*, (2010) who observed no obvious difference in various P treatments. In contrast, later phonological events (days to anthesis and physiological maturity) responded positively to applied P as well as AMF. Moreover, Ali *et al.*, (2019) also confirmed the positive results and reported that plant phenology was optimized with the co-application of organic and inorganic P sources.

AMF incorporation improves wheat physiological parameters. The addition of AMF increased SPAD value by 2.79%. Likewise, LAI was enhanced by 11.17% in AMF-amended plots. AMF have been shown to benefit crop growth and development due to their contribution to plant nutrition, soil structure, and other ecosystem services (Ortas and Bykova, 2018). AMF addition can enhance the wheat roots ability to absorb several nutrients, the improvement of nutrients uptake is attributed to the far-reaching and penetrable hyphal and mycelial system. AMF acts as a bridge for nutrient transportation between soil and roots, and hyphae can also assist roots in water uptake (Wahid *et al.*, 2016).

The optimum rate of P application plays a vital role in wheat growth. The results revealed that LAI was improved by 3.63% than the reduced P level. P is noted especially for the enhancement of photosynthetic ability (Akhtar *et al.*, 2015) and conversion of those useful plant compounds, required for optimum development and production (Rafique *et al.*, 2018). P deficiency is directly proportional to the discoloration of chlorophyll pigment (Jacob & Lawlor 1991) and the photosynthetic capacity reduction of the leaf (Zhu *et al*., 2012). The results corroborated by Wiens *et al.,* (2019) documented that the optimum P rate had a significant positive impact on wheat physiological parameters. Among different P sources, co-application of SSP and PM in the 50:50 ratio produced higher LAI which was statistically similar to sole SSP-applied plots. Similarly, the same treatment resulted in taller plants with higher SPAD values. P availability and concentration for plant use are often limited in calcareous soil although it is present in organic as well as in inorganic forms (Wahid *et al.,* 2016). The restricted availability is mostly owing to the fixation and complex formation with other nutrients (Shafi *et al.,* 2020). So, wisely integration of these available P sources is indispensable for the limited on-farm resources to sustain crop productivity on a sustainable basis with lower environmental costs.

Soils having high calcium and carbonate contents reduce P solubility and form complex P compounds (Shafi *et al.,* 2020). Field studies showed that AMF incorporation had a significant positive impact on yield and yield components. An increase of 5.2% in wheat and 10.1% in subsequent maize grain yield has been recorded with AMF when compared with no-AMF-added plots. Higher yield and biomass in AMF-amended plots were attributed to the protons release and extension of hyphae by AMF for P uptake and acquisition (Smith and Smith, 2011). Confirmatory results are documented by Efthymiou *et al.*, (2018) and Smith *et al.*, (2015) who found that wheat and maize productivity improved with AMF inoculation under field study. Likewise, Garmendia *et al.*, (2017) also confirmed the AMF vitality for sustainable wheat-maize productivity even under a range of environments. A comprehensive study performed by Gupta and Abbott, (2020) for AMF-inoculated cereals, documented that AMF inoculation had a positive effect on root colonization for essential nutrients uptake and overall wheat productivity (Zhang et al. 2019; Ryan et al. 2019).

In a similar manner, 90 kg ha^{-1} P application produced a higher grain yield than 60 kg ha^{-1}. As the P application level increased in the present study, all the yield attributes showed a positive response. P availability to plants can optimize several physiological processes; photosynthesis, respiration (Noonari *et al.*, 2016), storage of energy, and cell division (Bakhsh *et al.*, 2008). Comparing various P sources, the addition of P from SSP+PM in a 50:50 ratio produced higher grain yield for both crops which was followed by sole SSP application. Several studies on the integration of organic and synthetic P sources reported more noticeable outcomes in cereal-based cropping systems than the use of a single source (Zafar *et al.* 2017). The benefits of combined P management were not limited to improving grain yield and its attributes (Venkatesh et al., 2019), as on-farm available organic amendments incorporation adds organic matter content to the soil which can positively influence soil microbial activity and diversity. Consequently, the use of diverse P sources (organic amendments and synthetic fertilizer) along with P solubilizing bio-fertilizers has been encouraged on several occasions (Ali *et al.*, 2020; Kaur and Reddy, 2015).

Conclusions and Recommendations

Considering results and discussion, it is concluded that AMF incorporation improved phenological events and grain yield (3875 kg ha^{-1}) of wheat and subsequent maize (3669 kg ha^{-1}). Likewise, it also had a positive impact on the SPAD value (55) and LAI (3.84) of wheat, compared to the no-addition of AMF.

P management revealed that co-application of SSP+PM in a 50:50 ratio at the rate of 60 kg ha^{-1} reported optimum days to physiological maturity, SPAD value (50), LAI (3.54), and wheat-maize productivity. Sole application from SSP at the rate of 90 kg ha^{-1}also performed better and reported statistically similar results for the said parameters.

Based on the conclusion, the combined application of SSP and PM at the rate of 60 kg ha^{-1} along with AMF incorporation had more potential to improve wheat-maize productivity on a sustainable basis in P-deficient calcareous soils.

Data availability

The data that support the findings of this study are listed in the article and are available from the corresponding authors upon reasonable request.

Acknowledgment

The authors greatly acknowledge the Higher Education Commission (HEC) of Pakistan for providing research scholarship and funds under the HEC indigenous 5000 PhD Fellowship Program Batch-III, Phase-II with the support of which this research work was successfully conducted.

Declaration of Interest

We declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere. The authors certified that there are no conflicts of interest associated with this publication, and there has been no significant financial support for publishing this work that could have influenced its outcome. As corresponding Author, I conform that the manuscript has been read and approved for submission by all the named authors.

References

Akhtar.M., M. Yaqub, A. Naeem, M. Ashrafb and V. E. H. ernandez. 2016. Improving phosphorus uptake and wheat productivity by phosphoric acid application in alkaline calcareous soils. Sci Food Agric. 96: 3701-3707 https://doi.org/10.1002/jsfa.7555

Ali, M., Inamullah, M. Bilal, S. Ali, F. Nawaz and M.O. Iqbal. 2019. Soil physical properties, total N and maize yield response to various N sources incorporated with different tillage implements. Sarhad J. of Agric. 35(1): 216-224 http://dx.doi.org/10.17582/journal.sja/2019/35.1.216.224

Ali, M., Inamullah, S. Ahmad and A. Khan. 2018. Nitrogen sources incorporation with different tillage implements affects maize productivity and soil organic matter. Sarhad J. of Agric., 34(2): 478-485 http://dx.doi.org/10.17582/journal.sja/2018/34.2.478.485

Ali, S., M. Arif, M. Ali, M. Afzaal, G. Saeed, M. Bilal, F. Munsif and S. Zaheer. 2020. Biochar and integrated phosphorus management suppress weed density in maize crop. Pak. J. Weed Sci. Res., 26(4): 491-497 https://doi.org/10.28941/pjwsr.v26i4.911

Aslam, M. 2016. Agricultural productivity current scenario, constraints and future prospects in Pakistan. Sarhad J. Agric., 32(4): 289-303 http://dx.doi.org/10.17582/journal.sja/2016.32.4.289.303

Bakhsh, A., R. Khan, A.R. Gurmani, M.S. Khan, M.S. Nawaz, F. Haq and A.Farid. 2008. Residual/direct of phosphorus application on wheat and rice yield under rice-wheat system. Gomal Uni. J. of Res., 24: 29-35.

Bakhshandeh, S., E. Paola, P. Corneoa, Mariottea, M. A. Kertesza, A. Feike and Dijkstraa. 2017. Effect of crop rotation on mycorrhizal colonization and wheat yield under different fertilizer treatments. Agric. Ecosys & Environ., 247: 130-136 https://doi.org/10.1016/j.agee.2017.06.027

Behlr. R. K., H. Sharma, V. Kumar and K. P. Singh. 2015. Effect of dual inoculation of VA mycorrhiza and azotobacter chroococcum on above flag leaf characters in wheat. Archives of Agron. & Soil Sci., 79: 29-36 https://doi.org/10.1080/03650340301497

Campos, P., F. Borie, P. Cornejo, J.A. López-Ráez, A. López-García and A. Seguel. 2018. Phosphorus acquisition efficiency related to root traits: is mycorrhizal symbiosis a key factor to wheat and barley cropping. Front. Plant Sci., 9:752-759 https://doi.org/10.3389/fpls.2018.00752

Cavagnaro, T.R., S.F. Bender, H.R. Asghari, and M.G. Van der Heijden. 2015. The role of arbuscular mycorrhizas in reducing soil nutrient loss. Trends Plant Sci., 20: 283–290 https://doi.org/10.1016/j.tplants.2015.03.004

Efthymiou, A., B. Jensenand and I. Jakobsen. 2018. The roles of mycorrhiza and Penicillium inoculants in phosphorus uptake by biochar-amended wheat. Soil Bio. Biochem. 127: 168-177 https://doi.org/10.1016/j.soilbio.2018.09.027

FAO, 2020. Food and Agriculture Organization of the United Nations. FAO. URL http://faostat3.fao.org.(Accessed 02 May 2020).

Garmendia, I., Y. Gogorcena, I. Aranjueloand N. Goicoechea. 2017. Responsiveness of durum wheat to mycorrhizal inoculation under different environmental scenarios. J. of Plant Growth Regulation, 36(4): 855-867. https://doi.org/10.1007/s00344-017-9690-x

Gupta, M. M., & Abbott, L. K. (2021). Exploring economic assessment of the arbuscular mycorrhizal symbiosis. *Symbiosis*, *83*(2): 143-152.

Hussain, S., M. Sharif, S. Khan, F. Wahid, H. Nihar, W. Ahmad, I. Khan, N. Haider and T. Yaseen. 2016. Vermicompost and mycorrhiza effect on yield and phosphorus uptake of wheat crop. Sarhad J. of Agric., 32(4): 372-381. http://dx.doi.org/10.17582/journal.sja/2016.32.4.372.381

Inamullah and A.A. Khan. 2015. Plant nutrition. *In*: Agriculture The Basics 3rd ed. pp.164-165.

Jacob, J. and D.W. Lawlor. 1991. Stomatal and mesophyll limitations of photosynthesis in phosphate deficient sunflower, maize and wheat plants. J. of Experi. Bot. 42: 1003-1011. https://doi.org/10.1093/jxb/42.8.1003

Jan, B.,A. Ali, F. Wahid, S. N. M. Shah, A. Khan and F. Khan.2014. Effect of Arbuscular Mycorrhiza fungal inoculation with compost on yield and phosphorous uptake of berseem in alkaline calcareous soil. Amer. J. of Plant Sci., 5: 1359-1369. http://dx.doi.org/10.4236/ajps.2014.59150

Jan, M.T., P. Shah, P.A. Hoolinton, M.J. Khan and Q. Sohail. 2009. Agriculture research: Design and Analysis: A monograph Deptt. ofAgron., NWFP Agric. Uni. Peshawar, Pakistan.

Kaur, G. and M.S. Reddy. 2015. Effects of phosphate-solubilizing bacteria, rock phosphate and chemical fertilizers on maize-wheat cropping cycle and economics. Pedosphere 25: 428-437. https://doi.org/10.1016/S1002-0160(15)30010-2

Khalil, S.K., S. Khan, A.Rahman, A.Z. Khan, I.H. Khalil, I.H., Amanullah, S. Wahab, F. Mohammad, S.Nigar, M.Zubair, S. Parveen and A. Khan. 2010. Seed priming and phosphorus application enhance phenology and dry matter production of wheat. Pak. J. Bot., 42(3):1849-1856.

Manimaran, M. 2014. Integrated phosphorus management in maize crop grown in alkaline soil. Int. J. Mod. Sci. Eng. Tech., 1(6): 53-56.

MNFSR. 2019.Agricultural Statistics of Pakistan 2018-2019. Ministry of National Food Security and Research (Economic Wing) Government of Pakistan Islamabad.

Noonari, Shahzado, S.A. Kalhoro, A. Ali, A. Mahar, S. Raza, M. Ahmed, S.F.A Shah and S.U. Baloch. 2016. Effect of different levels of phosphorus and method of application on the growth and yield of wheat. Natural Sci. 8 (7): 305-314. http://dx.doi.org/10.4236/ns.2016.87035

Ortas, I. and A. Bykova. 2018. The effect of mycorrhiza inoculationand phosphorus application on phosphorus efficiency of wheat plants. Comm. in Soil Sci. Plant Anal. 49(1):1-10 https://doi.org/10.1080/00103624.2018.1455849

Pellegrino, Elisa, M. Öpik, E. Bonari and L.Ercoli. 2015. Responses of wheat to arbuscular mycorrhizal fungi: a meta-analysis of field studies from 1975 to 2013. Soil Bio Biochem. 84: 210-217. https://doi.org/10.1016/j.soilbio.2015.02.020

Rafique, R., Z. Zahra, N. Virk, M. Shahid, E. Pinelli, J. Kallerhoff, T.J. Park and M. Arshad. 2018. Data on rhizosphere pH, phosphorus uptake and wheat growth responses upon TiO2 nanoparticles application. Data in brief, 17: 890-896. https://doi.org/10.1016/j.dib.2018.02.002

Ryan, M.H., J.H. Graham, J.B. Morton, J.A. Kirkegaard. 2019. Research must use a systems agronomy approach if management of the Arbuscular mycorrhizal symbiosis is to contribute to sustainable intensification. New Phytol 222(3):1176–1178

Saharan, V., R. Kumaraswamy, R.C. Choudhary, S. Kumari, A. Pal, R. Raliya and P. Biswas. 2016. Cu-Chitosan nanoparticle mediated sustainable approach to enhance seedling growth in maize by mobilizing reserved food. J. Agric. Food Chem. 64: 6148-6155. https://doi.org/10.1021/acs.jafc.6b02239

Saikia, P., S.S. Bhattacharya and K.K. Baruah. 2015. Organic substitution in fertilizer schedule: Impacts on soil health, photosynthetic efficiency, yield and assimilation in wheat grown in alluvial soil. Agric. Ecosyst. Environ. 203: 102-109. https://doi.org/10.1016/j.agee.2015.02.003

Shafi, M.I., M. Adnan, S. Fahad, F. Wahid, A. Khan, Z.Yue, S. Danish, M. Zafar-ul-Hye, M. Brtnicky and R. Datta. 2020. Application of single superphosphate with humic acid improves the growth, yield and phosphorus uptake of wheat (*Triticum aestivum* L.) in calcareous soil. Agron., 10(9): 1224, 1-15 https://doi.org/10.3390/agronomy10091224

Shahzad, K., A. Khan, J.U. Smith, M. Saeed, S. A. Khan and S.M. Khan. 2015. Residual effects of different tillage systems, bioslurry and poultry manure on soil properties and subsequent wheat productivity under humid subtropical conditions of Pakistan. Int'l. J. of Biosci., 6(11): 99-108.

Sharif, M., S. Saud, T.Burni, M.Afzal, F. Khan, M.J. KhanandF. Wahid. 2012. Effect of arbuscular mycorrhizal fungal inoculation in combination with different organic fertilizers on maize crop in eroded soils. Pak. J. Bot., 44(4): 1427-1432.

Smith, S.E. and F.A. Smith. 2011. Roles of arbuscular mycorrhizas in plant nutrition and growth. New paradigms from cellular to ecosystem scales. Annu. Rev. Plant Biol. 62: 227–250.

Smith, S.E., M. Manjarrez, R.Stonor, A. McNeill andF.A. Smith. 2015. Indigenous arbuscular mycorrhizal (AM) fungi contribute to wheat phosphate uptake in a semi-arid field environment, shown by tracking with radioactive phosphorus. Appl. Soil Eco., 96: 68-74.

Uwah, D.F., F.A. AfonneandA.R. Essien. 2011. Integrated nutrient management for sweet maize (*Zea mays*(L.) saccharata Strut.) production in calabar, Nigeria. Aus. J. of Basic and App. Sci., 5(11): 1019-1025.

Wahid, F., M. Sharif, S. Steinkillner, M. Azim Khan and K.B. Marwat. 2016. Inoculation of Arbuscular mycorrhizal fungi in presence of rock phosphate improve phosphorus uptake and growth of maize. Pak. J. Bot., 48(2): 739-747.

Wiens, J.T., B.J. Cade-Menun, B. Weiseth, andJ.J. Schoenau. 2019. Potential phosphorus export in snowmelt as influenced by fertilizer placement method in the Canadian Prairies. J. of Environ.Quality, 48(3): 586-593. https://doi.org/10.2134/jeq2018.07.0276

Yousefi, A.A., K. Khavazi, A.A. Moezi, F. Rejali and H.A.Nadian. 2011. Phosphate solubilizing bacteria and arbuscular mycorrhizal fungi impacts on inorganic phosphorus fractions and wheat growth. World Appl. Sci. J. 15 (9): 1310-1318.

Zafar, M., M.S. Rizwan and M. Shahid. 2017. Introduction of composted rock phosphate and poultry manure enhances winter wheat phosphorus use efficiency, grain yield and soil quality. J. Plant Nut. 40(13): 1887-1899. https://doi.org/10.1080/01904167.2016.1270316

Zavattaro, L., L. Bechini, C. Grignani, F.K. van Evert, J. Mallast, H. Spiegel, T. Sanden, A. Pecio, J.V. GiraldezCervera, G. Guzman, K. Vanderlinden, T. D'Hose, G. Ruysschaert and H.F.M. ten Berge. 2017. Agronomic effects of bovine manure: A review of long-term

European field experiments. Eur. J. Agron. 90: 127-138. https://doi.org/10.1016/j.eja.2017.07.010

Zhang, S., A. Lehmann, W. Zheng, Z. You and M.C. Rillig. 2019. Arbuscular mycorrhizal fungi increase grain yields: a meta-analysis. New Phytol 222(1): 543–555.

Zhu, X., C. Li, Z. Jiang, L. Huang, C. Feng, W. Guoand and Y. Peng. 2012. Responses of phosphorus use efficiency, grain yield, and quality to phosphorus application amount of weak-gluten wheat. J. of Integ. Agric., 11(7): 1103-1110 https://doi.org/10.1016/S2095-3119(12)60103-8