

Effects of Phosphorus Application on Agro-morphological Traits, Seed Quality, and Phosphorus Use Efficiency in *Sinapis alba* L. under Rain-fed Conditions

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ABSTRACT

White mustard (*Sinapis alba* L.) is an emerging crop belonging to the Brassicaceae family, offering an alternative to other oilseed crops suitable for dry temperate climates. In current study, the impacts of phosphorus (P) fertilizer on agro-morphological and seed quality components of white mustard were investigated. The Australis cultivar was planted in P-deficient soil, with seven treatments ranging from T1-Control to T7-70 kg ha⁻¹. Each treatment was replicated four times, following a randomized complete block design (RCBD). The results revealed significantly increase for number of seeds per silique (NSP), thousand seed weight (TSW), biological yield (BY), seed yield (SY), harvest index (HI), and oil yield (OY) by 51%, 56%, 70%, 49%, 60%, and 36%, respectively, compared to the control treatment when P fertilizer was applied at 70 kg ha⁻¹. Furthermore, protein (PC) and oil contents (OC) also showed significant increase of 87% and 80%, respectively, compared to the control, while glucosinolate contents (GSC) decreased by 75%. Similarly, at the 70 kg ha⁻¹ doses, phosphorus use efficiency (PUE), physiological efficiency (PE), apparent recovery efficiency (ARE), and agronomic efficiency (AE) reached maximum values, improving by 34%, 50%, 39%, and 31%, respectively, compared to the control. A positive linear relationship was observed between seed yield and agro-morphological attributes, quality characteristics, and P use efficiencies. In conclusion, the addition of P fertilizer proved beneficial in enhancing growth and P uptake, resulting in increased seed yield of *S. alba* in the rainfed region of Pothwar, Pakistan.

Keywords: white mustard, phosphorus fertilization, seed quality, phosphorus use efficiency, oil seed production.

INTRODUCTION

Oil seed crops are pivotal to the Pakistan economy; however, the production of edible oil from these crops falls short of meeting the demand. The insufficient yield of oilseed crops in Pakistan can be attributed to a range of factors, including inappropriate policies, farmers' limited knowledge and interest in cultivating oilseed crops, reliance on traditional cultivation methods, as well as biotic and abiotic factors, along with technological deficiencies (Khan et al., 2021). *Sinapis alba* growth characteristics, adaptability, and drought resistance have been extensively studied by (Jankowski et al.,

2020), making it a strong option for cultivation in challenging environments. Its effective self-incompatibility mechanism, increased genetic diversity, and physical traits suited to dry, temperate regions (Gennari et al., 2019) offer several advantages over oilseed rape, notably by improving its ability to withstand moisture deficits, heat, frost, and pests (Wilczewski et al., 2019). The plant's deep root system (Jakubus and Bakinowska, 2020), fast growth, and significant dry matter output (Wanic et al., 2019), highlight its versatility. With broad leaves and high nutritional value, *S. alba* is a valuable livestock fodder source, and it is also attractive to honey bees, adding appeal for

apiculture (Grygier, 2023). Additionally, its hybridization potential increases its significance in agronomic practices (Kumari et al., 2020). The strong dehiscence zone in *S. alba* siliquae enhances their resistance to shattering at maturity, while their compatibility with mechanical harvesting provides additional benefits (Mitrović et al., 2020). These characteristics are beneficial in regions with limited moisture, positioning *S. alba* as a highly suitable crop for semi-arid climates, such as those found in Pakistan.

Phosphorus is the second rarest essential macronutrient for plants, behind nitrogen. Phosphorus is important for a multitude of biological activities that take place in all living organisms. It has a vital role in nucleic acids and cellular membranes, serving as a crucial element in photosynthesis, energy preservation, carbon metabolism, cell interaction, and as a catalyst in other biological processes (de Bang et al., 2021). Phosphorus enhances crop quality by stimulating plant growth and development, flowering and seed formation, and resistance to diseases. Plants have developed diverse and intricate metabolic and developmental strategies to enhance the uptake and redistribution of phosphorus in situations where phosphorus is limited (Begum et al., 2019). The primary manifestations of phosphorus (P) deficiency in plants are reduced shoot growth, decreased root proliferation, and modified root structure (Niu et al., 2013; Grover et al., 2021). The response of plants to phosphorus (P) stress is a protective mechanism that preserves the phosphorus concentration in the leaves. This is achieved by inhibiting shoot development and promoting phosphorus absorption through increased root growth (Plaxton and Carswell, 2018). Optimizing phosphorus fertilization has therefore become an essential component of sustainable crop production. Recent studies have demonstrated that balanced phosphorus fertilization significantly improves crop productivity and nutrient use efficiency under different soil and climatic conditions, highlighting the importance of appropriate phosphorus management for sustainable agricultural systems (Uyeturk et al., 2023; Chipier et al., 2024). Likewise,

long-term fertilizer experiments have confirmed that balanced phosphorus nutrition contributes to stable crop performance and improves the efficiency of applied nutrients across contrasting environments (Chipier et al., 2024).

Improving phosphorus use efficiency (PUE) has become increasingly important because phosphate resources are finite and excessive fertilizer application increases production costs and environmental risks. Recent research has shown that efficient nutrient management strategies enhance crop productivity while improving fertilizer use efficiency and reducing nutrient losses (Constantinescu et al., 2023). *Sinapis alba* is an exotic crop which is not being grown at commercial scale in the country. Hence, aspect of its growing is yet not cleared to the farming community. Apart from its basic agronomic techniques for growing at large scale, nutrients requirements under local condition have not been explored yet. In particular, no comprehensive study has evaluated the combined effects of phosphorus fertilization on agro-morphological traits, seed quality, and phosphorus use efficiency of *S. alba* grown under phosphorus-deficient rain-fed soils of the Pothwar region.

MATERIAL AND METHODS

Experimental site, climate, and soil conditions

The experiments were place at PMAS-Arid Agriculture Research Farm Koont, situated on Chakwal Road, Rawalpindi. The farm is located at a latitude of 33.3°N, a longitude of 73.3°E, and an elevation of 460 meters above sea level. Field experiments were done in the Rabi seasons of 2019-20 and 2020-21 to study the optimal levels of phosphorus and their effects on the growth, yield, and phosphorus efficiency of *S. alba*. The site has a typical desert environment, with an average yearly temperature of 22.7°C, an average yearly rainfall varies between 650 to 850 mm, and an average yearly potential evaporation of 900 mm. The annual solar radiation is 5988 M J m⁻², and the frost-free period spans from day 170 to day 180.

The soil is categorized as sandy clay loam and belongs to the Aridisol soil order. Before the experiment began, the soil (0-30 cm) had a pH of 7.85, a soil organic matter content of 0.75 g kg⁻¹, a total nitrogen (N) concentration of 3.75 mg kg⁻¹, an Olsen-P concentration of 3.79 mg kg⁻¹, and a plant-available potassium (K) concentration of 185 mg kg⁻¹ (Haq et al., 2023). In late September, the soil was tilled thrice under ideal moisture conditions. During the final preparation, the soil was enriched with appropriate quantities of nitrogen (70 kg ha⁻¹), phosphorus (35 kg ha⁻¹), and potassium (25 kg ha⁻¹) using urea, single super phosphate (SSP), and sulfate of potash (SOP) as fertilizers. In order to investigate the impact of phosphorus, a crucial nutrient, on *S. alba*, seven different amounts of phosphorus were examined: T1 (Control, no phosphorus), T2 (20 kg ha⁻¹), T3 (30 kg ha⁻¹), T4 (40 kg ha⁻¹), T5 (50 kg ha⁻¹), T6 (60 kg ha⁻¹), and T7 (70 kg ha⁻¹). Prior to sowing, these levels were implemented using single super phosphate (SSP, 18%) as the source of phosphorus.

The sowing process was carried out using a manual drill, with the seeds being applied at a pace of 5 kilograms per hectare. The row-to-row spacing was consistently set at 30 cm, while the plant-to-plant spacing was kept at 15 cm. This spacing arrangement was maintained after the germination process. The experimental design used a randomized complete block design (RCBD) with three replications. Sowing was conducted on October 5, 2019, and October 5, 2020. Each treatment plot occupied a 10 m² space. Thinning was conducted at the three-leaf stage, plant density was maintained at 23 plants m⁻². Weeds were controlled manually after crop emergence whenever necessary, and no herbicides were applied. The crop was regularly monitored for insect and diseases infestation: however, no insecticide and fungicides were applied during the growing seasons. The experiment was conducted under entirely rainfed region of pothwar, with no supplemental irrigation provided throughout the growing season of experiment. All other crop management practice was kept uniform

in all treatments. Measurements were taken during the physiological maturity phase. The harvest occurred when the crop achieved full maturity on April 20, 2020, and April 26, 2021.

Agro-morphological and quality parameters

After harvesting, the number of siliques per plant (NSP) was measured by counting siliques from ten randomly selected plants in each treatment plot, and then calculating the average. A sub-sample of seeds were taken to measure thousand-seed weight (TSW). The plants were harvested and weight to measure biological yield (BY) and thresh to measure grain yield. Moreover, harvest index (HI) was measured as ratio of grain and biomass yield. The oil yield was measured with following formula: $OY = OC \times SY/100$. Seed oil, protein, and glucosinolate contents were evaluated through near-infrared reflectance spectroscopy (NIRS) (Sato et al., 2008).

Phosphorus use efficiency

Phosphorus use efficiency (PUE) was calculated as Zhang et al. (2020). The following equation was used to calculate by the Phosphorus use efficiency:

$$PUE = \frac{DM(f) - DM(c)}{FD}$$

Physiological Efficiency

The following equation was used to determine biological production per unit of applied fertilizer is as follows:

$$PE = \frac{DM(f) - DM(c)}{NU(f) - NU(c)}$$

Apparent Recovery Efficiency

The following equation was used to calculate the quantity of nutrient uptake per unit of nutrient applied:

$$ARE = \frac{NU(f) - NU(c)}{FD} \times 100$$

Agonomic Efficiency

The following equation was used regarding the seed yield obtained per unit of nutrient applied:

$$AE = \frac{SY(f) - SY(c)}{FD}$$

Here, DM (f) indicates dry matter yield of fertilized plots, DM (c) shows the dry matter yield of controlled plots. Moreover, FD shows dose of fertilizers and NU (f), NU (c), SY (f) and SY (c) shows nutrients uptake in fertilizers and controlled plots and seed yield in fertilized and controlled plots.

Statistical analysis

The data analysis was performed using Statistics 8.1 software by using analysis of variance. Moreover, LSD (least significant difference) was used to compare treatment means at 5% probability level (Steel and Torrie, 1980). The Pearson's correlation was performed to measure the trait relationships using R studio. The figures were made by using Origin Pro version 2021. The response to different doses of P fertilizer was evaluated using a quadratic regression model. This model was employed to analyze agro-morphological and qualitative indices, as well

as phosphorus utilization efficiencies.

RESULTS AND DISCUSSION

Phosphorus fertilization effects on agro-morphological parameters of *S. alba*

Phosphorus fertilizer expressed the positive results regarding increase in the number of siliques per plant NSP of *S. alba* up to the 70 kg ha⁻¹ (Figure 2 a). During 2019-20, the maximum (5.3) NSP was calculated from T7 (70 kg ha⁻¹ P), while the minimum (3.17) obtained from T1 control.

Phosphorus fertilizer levels showed progressive increase for thousand seed weight (TSW) during both years (Figure 2b). During 2019-20, the maximum (5.87 g) TSW was observed from T7 (70 kg ha⁻¹ P) while the minimum (3.3 g) TSW from T1 (control). Same trend was also observed during 2020-21, where maximum TSW was (5.67g) and minimum TSW (3.37g).

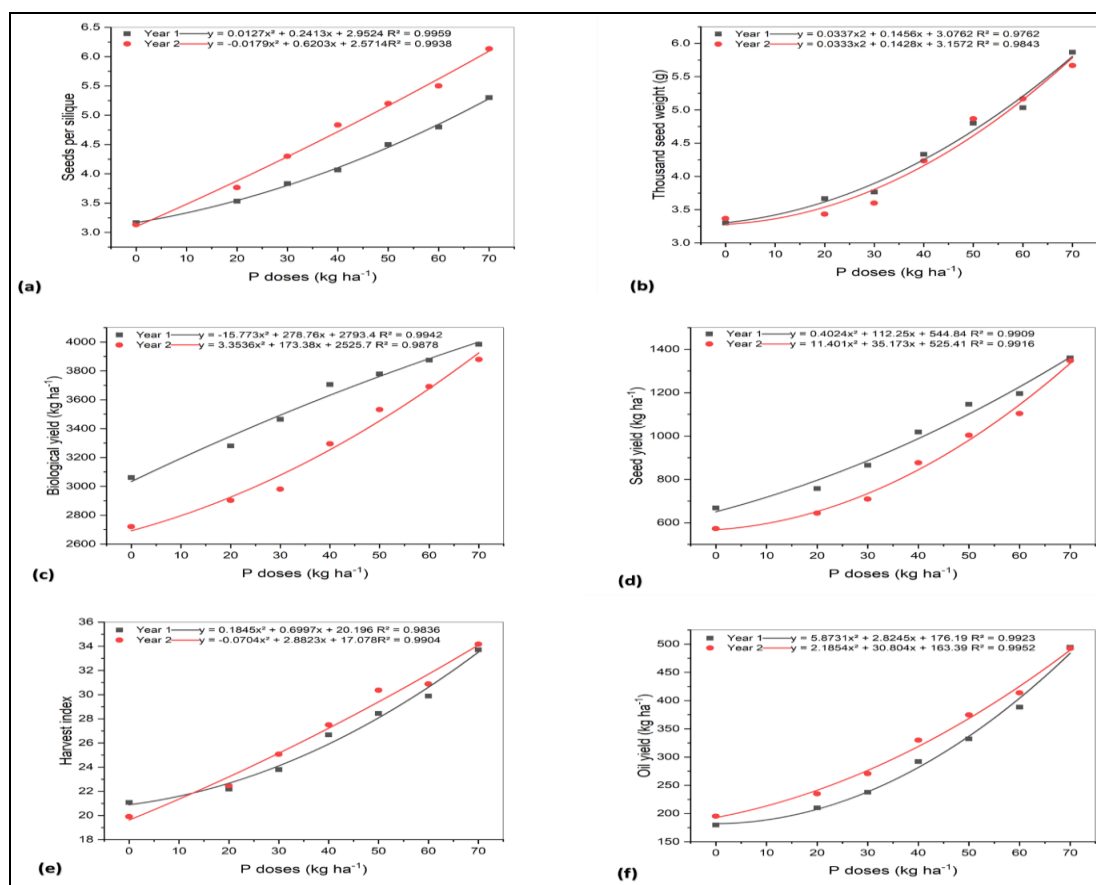


Figure 1. The quadratic curve model was applied to assess the impact of different phosphorus (P) doses on various agro-morphological characteristics, including (a) the number of seeds per silique, (b) 1000 seed weight, (c) biological yield, (d) seed yield, (e) harvest index (H.I %), and (f) oil yield. This study was executed in two years, 2019-20 and 2020-21. The lines in the graphs illustrate the correlation of agro-morphological attributes and varying P doses, along with a 95% confidence interval. The coefficient of determination (R²) indicates the model's goodness of fit.

During 2019-20 the highest BY (3879.7 kg ha⁻¹) was obtained from T7 (70 kg ha⁻¹ P) while the minimum BY (2720.9 kg ha⁻¹) was observed from T1 (control: Figure 2c). During (2020-21), the general trend remained same with maximum and minimum BY, yet

the highest BY (3984.5 kg ha⁻¹) from T7 and lowest (3361.6.7 kg ha⁻¹) from T1 was obtained. However, during 2019-20 first three treatments (T1-T3) did not differ significantly from each other but were significantly different from (T4-T7).

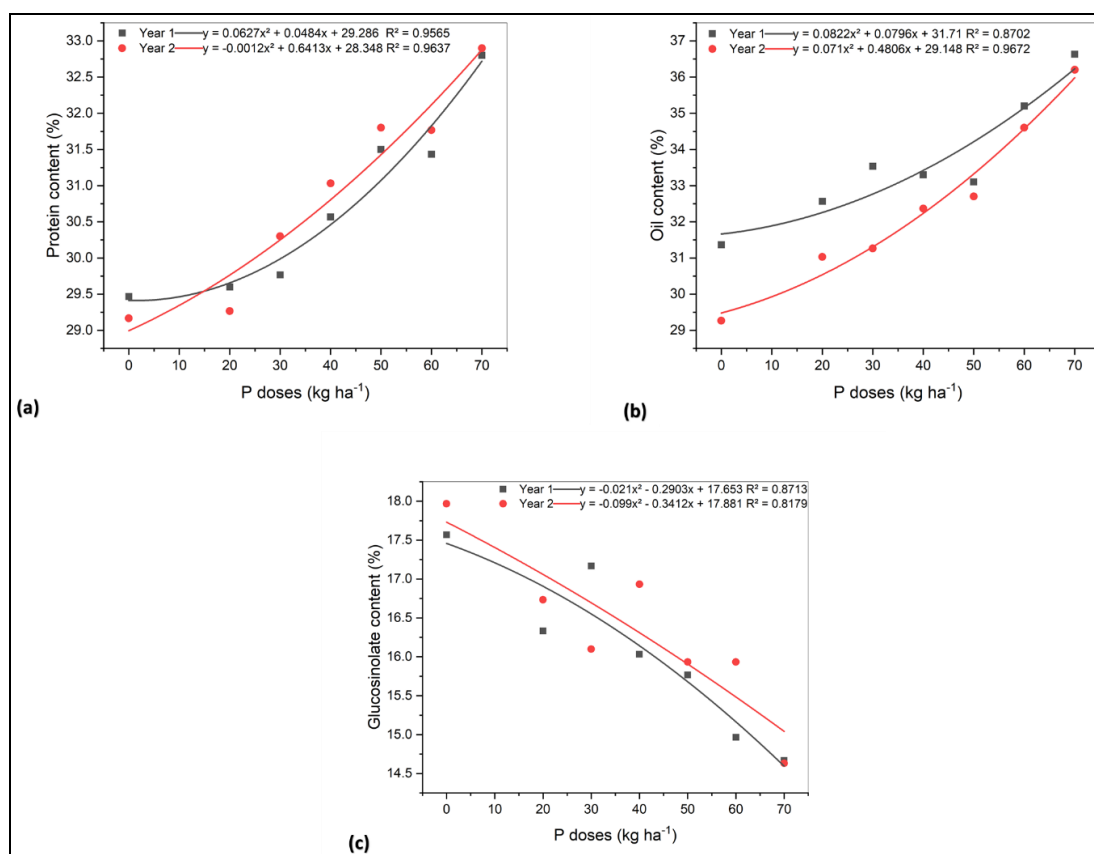


Figure 2. The quadratic curve model was applied to assess the impact of different phosphorus (P) doses on various seed quality parameters, including (a) protein content, (b) oil content and (c) glucosinolate content. This study was executed in two years, 2019-20 and 2020-21. The lines in the graphs illustrate the correlation between agro-morphological attributes and varying P doses, along with a 95% confidence interval. The coefficient of determination (R^2) indicates the model's goodness of fit.

The increase in P caused the progressive increase in the seed yield (SY) up to the 70 kg ha⁻¹ P. During 2019-20 highest SY (1348.1 kg ha⁻¹) was obtained from T7 (70 kg ha⁻¹) and the minimum SY (572.8 kg ha⁻¹) attained from the control and similar trend was observed during 2020-21. Increase in the level of P caused the gradually increase in HI of *S. alba* up to the T6 (70 kg ha⁻¹ P). The highest (34.71) HI during 2019-20 was noted at the highest level of P application while the minimum (21.07) was recorded from control. Almost the same trend was also observed during 2020-21, where the maximum (34.18) HI was observed from T7 while the minimum

(19.91) from control. Moreover, same treatments from both years were not statistically significant from each other (Figure 2e).

Application of phosphorus showed progressive increase of oil yield (OY) up to 70 kg ha⁻¹. All treatments significantly increased the OY as compared to the control during both years of experiments (Figure 2f). During 2019-20, the maximum (494.4 kg ha⁻¹) OY obtained from T7 (70 kg ha⁻¹) while minimum observed from control (179.84 kg ha⁻¹). However, during 2020-21 the general trend remained the same with lower OY obtained from control, yet maximum OY in T7.

Phosphorus fertilization effect on quality parameters of *S. alba*

Protein content (PC) showed an increasing trend with increasing the P application in both experimental years. During 2019-20, the highest (32.8%) PC was recorded at T7 (70 kg ha⁻¹), while a similar trend was observed at T7 (32.9%) during 2020-21, while the lowest obtained from T1 control. However, the differences among the treatment's means were not statistically significant across the two years (Figure 3a). Oil content (OC) also showed the same trend with increasing the application of P increases in oil content (Figure 3b). During 2019-20, maximum (36.63%) oil contents (OC) were observed in

T7 (70 kg ha⁻¹ P) while a similar trend was observed at T7 during 2020-21. However, the differences among the treatment's means were not statistically significant across the two years. In contrast, glucosinolate content (GSC) showed a negative relationship with P application. The results indicated a substantial difference between T1 and T2 over the years. In the 2019-20 period, the highest GS content (17.27%) was observed in T2 (20 kg ha⁻¹), while the lowest GS content (13%) was noted in T7 (70 kg ha⁻¹). Furthermore, the findings also showed that during 2020-21, after reaching 40 kg ha⁻¹ P, GSC gradually decreased up to T7 (Figure 3c).

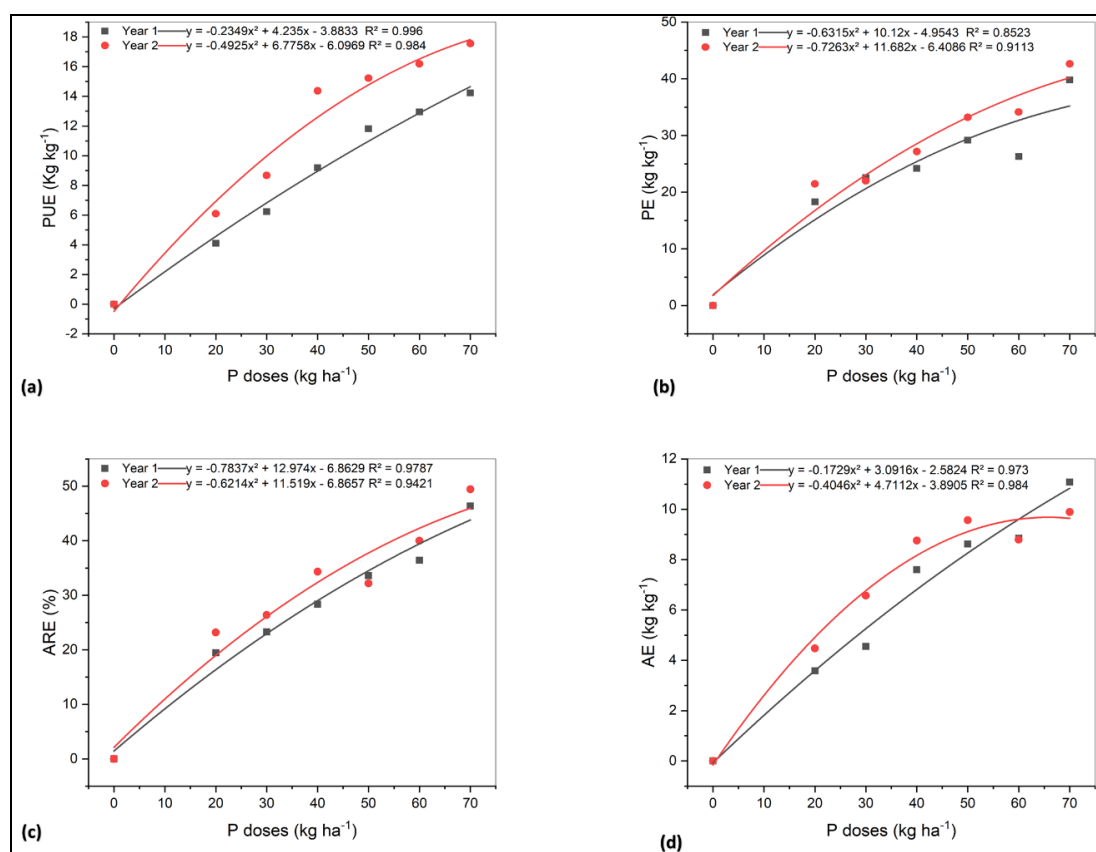


Figure 3. The quadratic curve model was applied to assess the impact of different phosphorus (P) doses on various phosphorus use efficiencies, including (a) phosphorus use efficiency, (b) physiological efficiency, (c) apparent recovery efficiency, and (d) agronomic efficiency. This study was executed in two years, 2019-20 and 2020-21. The lines in the graphs illustrate the correlation between agro-morphological attributes and varying P doses, along with a 95% confidence interval. The coefficient of determination (R^2) indicates the model's goodness of fit.

Phosphorus fertilization effect on phosphorus use efficiencies of *Sinapis alba*

Application of P showed progressive increase in phosphorus use efficiency (PUE) of *S. alba* up to 70 kg ha⁻¹. During 2019-20, highest PUE (14.23 kg/kg) was calculated

from T7 (70 kg ha⁻¹ P) while, minimum efficiency calculated from T2 (20 kg ha⁻¹). However, in general trend remained the same for the next year where maximum (17.55 kg/kg) was recorded at highest level of P and minimum from T2 (Figure 4a). Results

revealed that ARE was significantly increased by application of phosphorus fertilizer as compared to the control but the difference among the treatments was not significant (Figure 4b). During 2019-20 maximum (46.37%) ARE was obtained from T7 (70 Kg ha⁻¹ P) and the minimum was recorded in T2. During 2020-21 the maximum (49.44%) ARE was attained from T7 (70 kg ha⁻¹) and the minimum was obtained from T2. Results also elaborate that the difference among the treatments from both years was significant. During 2019-20, the maximum (39.78 kg/kg) PE was obtained from T7 (70 kgha⁻¹) and the minimum was recorded from T2. During 2020-21, the maximum (42.63 kg/kg) PE was attained from T7 (70 kgha⁻¹P) and the minimum from T2 (Figure 4c). Results also elaborate that the difference among the treatments from both years was significant. During 2019-20, the maximum (39.78 kg/kg) AE was obtained

from T7 (70 kgha⁻¹P) and the minimum was recorded from T2 (20 kg ha⁻¹). During 2020-21, the maximum (42.63 kg/kg) AE was attained from T7 (70 kgha⁻¹P) and the minimum T2 (Figure 4d).

Correlation among agronomic, seed quality and use efficiencies parameters

Seed yield (SY) exhibited significant ($p < 0.01$) and positive correlation with agro-morphological seed quality attributes i.e. NSP, TSW, BY, H.I, OY, OC and PC, as well with PUE, ARE, PE and AE in the current study (Figure 5). The optimal level of phosphorus 70 kg ha⁻¹ was the most probable reason of strongly positive correlation of vegetative units to enhances the seed yield of white mustard. Similarly, BY and PUE were significantly and positively correlated with these traits. However, BY, SY, HI, OY, OC, PC, PUE, PE, AE and ARE were negatively correlated with GSC.

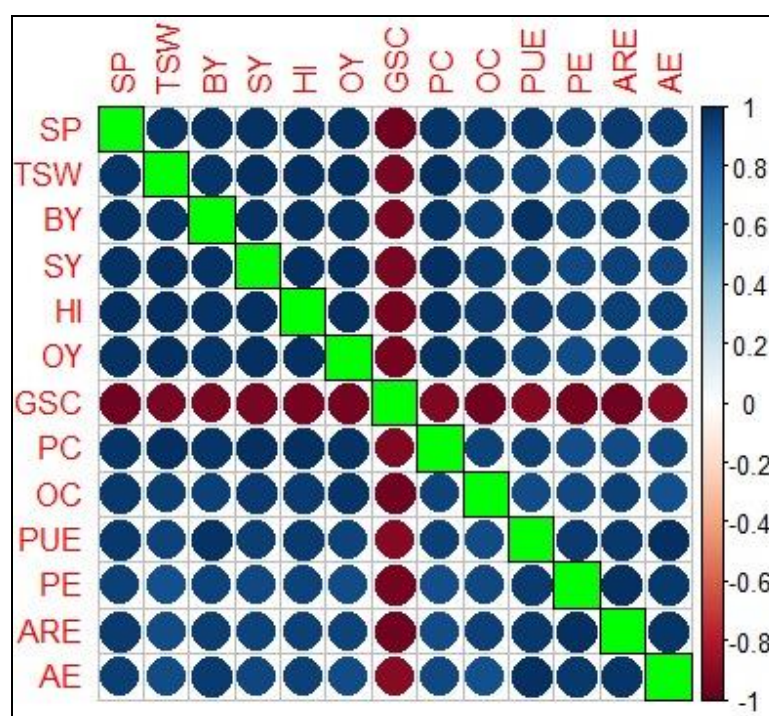


Figure 4. Pearson's correlation among agronomic, seed quality and use efficiencies parameters

Phosphorus plays a pivotal role as an essential nutrient for plant growth, demanding its incorporation into fertilizers globally, as highlighted by Liu et al. (2017). Its critical importance stems from being the most limiting nutrient, leading to a significant

decline in crop yields and posing a substantial challenge for agriculture in the 21st century (Fink et al., 2016). The data reveal that the optimum level 70 kg ha⁻¹ of P from both growing years (2019-20 and 2020-21) were statistically non-significant for first two

treatments and were significantly different among themselves in rest of the treatments. Using P fertilizer at different levels has ability to positively affect the growth and yield parameters of oil seed crops. In current study when the P was applied in *S. alba* the number of seeds per silique increased significantly, and the increment in seeds per silique was directly proportional to the level of P fertilizer. Almost similar results were reported by Wahid et al. (2014), who concluded that P fertilizer increased the number of seeds in the crop. According to Zangani et al. (2021) P fertilizer plays an important role for photosynthesis process in brassica crop and ultimate affect the growth of the crop. They also observed that the number of seeds per silique of brassica increased after application of P fertilizer.

Seed weight is considered an important parameter to estimate the yield of a crop. Furthermore, the results also revealed that increase in TSW was higher in 1st year as compared to the 2nd year. In current study, different levels of P fertilizer have significant impact on TSW in *S. alba*. By increasing the level of P TSW was also increased. These results are in line with the findings of Al-Juheishy et al. (2021), who concluded that different growth parameters including TSW was significantly related to the level of P fertilizer. Similarly, Jan and Khan (2000) also reported that the use of phosphorus fertilizer has positive impact on TSW in brassica crops.

Actually the biological yield is the dry matter accumulation of the crop. Usually increasing the overall yield of a crop necessitate to the increase BY of the crop. In current study, the application of P increased the BY of *S. alba*. At 70 kg ha⁻¹P level BY was more as compared to the lower level of P fertilizer. Similarly, Sharma et al. (2021) concluded that P significantly increased the dry matter. Phosphorus fertilizer is considered an important nutrient in increasing the yield parameters of mustard. When P was used on Indian mustard at different levels it increased the dry matter of the plant Cahyono and Minardi (2022). These results were also supportive to our findings.

Seed yield is affected by the application of different fertilizers. In current study, results showed that the seed yield increased by increasing the level of P. Effect of P fertilizer at different levels on seed yield of canola was also studied by Brennan and Bolland (2007), their findings are also supportive to our research as they reported increment in SY after application of P fertilizer. Similarly, When Liu et al. (2019) also observed significant increase of seed yield by the application of P fertilizer. Poor soil fertility is considered one of the main factors regarding the low production of food. In our country mostly intensive agriculture model is followed, so under such model the use P fertilizer is necessary to attain the targeted yield of crop (Fosu-Mensah and Mensah, 2016). At proper time the use of P in plant increases the growth by showing higher dry matter accumulation and harvest index (Amanullah et al., 2010). In current study, it was observed that HI of crop increased by applying the P fertilizer. The findings of Solanki et al. (2015) correlates with our results in which Phosphorous application has positive impact on HI of the crop was observed.

Application of P fertilizer improved the oil yield of *S. alba*. Our results are similar with findings of Potdar et al. (2019) who reported that the application of P significantly improved the oil content in mustard. However, Mishra et al. (2010) concluded similar findings, phosphorus fertilizer application in the mustard crop improved the oil content of seed. The findings demonstrated that the beginning and harvesting times of the rapid accumulation of dry matter in the *S. alba* were delayed with an increase in the phosphorus concentration, while the end time of the rapid accumulation was delayed to a greater extent. This led to a longer duration of the rapid accumulation of dry matter. The quick rate at which dry matter accumulated increased together with the buildup of phosphorus. Total biomass highly dependent on the synthesis and translocation of photosynthates towards different parts of the plant ultimately

determined the grain yield (Bellasio and Griffiths, 2014; Aneja et al., 2022).

Phosphorus is the basic element of protein which is an important structural component of all plants. In current study when the P fertilizer was applied on the crop of *S. alba* the protein content increased in the seed. The increase of PC was directly dependent upon the level of P. Our findings are supported by the study of Singh et al. (2018), who used S and P fertilizers on mustard and chickpea and concluded that application of P enhanced the protein contents in the seed. The study run by Harish et al. (2022) is also supportive to our findings as they concluded that the application of P significantly increased the PC. The comparison of the both growing years, the OC were generally higher from first year (2019-20) produce. The reason of high oil contents during 2019-20 as compared to the 2020-21 might be due to most suitable environmental conditions (Figure 1). The finding of Jat and Khangarot (2003), who concluded that by application of P the oil contents were increased in the crop. His findings are contradictory to our findings. The reason might be different environmental conditions or crop difference. However, Ismail and Hussain (2021) checked the effect of P fertilizer on mustard crop and concluded that the application of P increased the oil contents significantly. Moreover, results also shown that during 2020-21, after 40 kg ha⁻¹ P, glucosinolate contents gradually decreased up to T7. These observations are in line with the findings of Abd-el-All and El-Shabrawy (2013), who concluded that by application of P alone or in combination with nitrogen fertilizer improved the GS contents in brassica. Findings of Öztürk, (2021) are also supportive to our study as they also reported that the application of fertilizer causes the increase of GS contents.

Phosphorus is a critical nutrient essential for the healthy development of all crops. In our study, increasing phosphorus levels led to a notable improvement in phosphorus use efficiency (PUE). Our results are aligning with the findings of Zalak and Patel (2020), who also observed that higher phosphorus

inputs result in enhanced PUE. Interestingly, PUE was greater during the first growing season than the second, which may be explained by the higher average rainfall during the first season. These results are further supported by Yang et al. (2022), who highlighted that temperature plays a significant role in regulating nutrient uptake from the soil, thus affecting PUE.

Phosphorus, a vital nutrient, is integral to plant metabolic processes and contributes to energy transformation (Xie et al., 2016). In this study, diverse phosphorus levels significantly affected Apparent Recovery Efficiency (ARE). Similarly, Dwivedi et al. (2017), demonstrated that increased phosphorus availability in the soil enhances phosphorus use efficiency in mustard and groundnut crops. The observed higher ARE in 2019-20 compared to 2020-21 may be attributed to varying environmental conditions, with lower temperatures and higher humidity.

Phosphorus fertilizer faces challenges of low uptake efficiency, often remaining inaccessible to plants due to strong soil bonding (Veneklaas et al., 2012; Yahaya et al., 2023). Therefore, an optimal application is crucial for proper plant growth. Significant differences in physiological efficiency among various phosphorus fertilizer levels were noted, as reported by Cahyono and Minardi (2022) and Malhotra et al. (2018). Specific fertilizer levels contribute to plant vigor, with physiological efficiency (PE), directly tied to dry matter yield. DM accumulation depends on fertilizer utilization, and in this study, the optimum phosphorus level 70 kg ha⁻¹ resulted in elevated dry matter, ultimately increasing physiological yield. Seed yield, in turn, relies on fertilizer utilization. In this study, increasing phosphorus levels led to higher seed yield, supported by Ngo (2021), ultimately resulting in increased seed yield.

CONCLUSIONS

The results demonstrate that *Sinapis alba* has good potential for cultivation under the rain-fed agroecological conditions of the Pothwar region of Pakistan. Among the tested phosphorus rates, 70 kg P ha⁻¹ produced the

highest agronomic performance and phosphorus use efficiency, indicating that this rate may be suitable for white mustard production in the Pothwar region of Pakistan. These findings provide a useful basis for developing sustainable phosphorus fertilizer recommendations for this emerging oilseed crop. Nevertheless, further multi-location and multi-year studies are required to validate the optimum phosphorus requirement under diverse soil and climatic conditions.

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