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Efficacy of Rock Phosphate, Phosphate Solubilizing Bacteria and Chenopodium Album Aqueous Extract on Wheat Growth and Yield

Nourhan A. E. Saoud*, El-khawaga A.A.H, Salwa M.A.I. Ash-shormillesy, Eman Abdallah., Gomaa, F. S. M

Agronomy Dept., Fac. Agric., Zagazig Univ., Egypt, 44511

Corresponding author: Nourhan Saoud

E-mail: nourhan.soaud@gmail.com

Abstract

A two-season field experiment was conducted during 2020–2021 and 2021–2022 in Kafr Al-Naggar village, Abo Kabir District, Sharkia Governorate, Egypt, to investigate the effect of rock phosphate application, phosphate-solubilizing biofertilizer (phosphorien), and foliar application of Chenopodium album aqueous extract on growth, yield, yield components, and grain quality of wheat (Triticum aestivum L.) cultivar Misr-1. The experiment was arranged in a split-split plot design in three replications with three factors: rock phosphate application (0 and 300 kg/fad), phosphorien inoculation rates (0, 300, 600, and 900 g/seeds/fad), and spraying weed aqueous extract concentrations of C. album (0, 50%, and 100%). Results indicated that rock phosphate application had no significant effect on most studied traits, including grain yield and grain quality (crude protein content). In contrast, phosphorien inoculation significantly improved growth traits, yield components, grain yield, and grain protein content, with the highest response recorded at 900 g/seeds/fad (fad, Faddan= 4200m2). Similarly, foliar application of C. album extract significantly enhanced most agronomic traits, yield components, grain yield, and protein content, particularly at 100% concentration. Grain yield increased significantly under phosphorien inoculation and foliar spray treatments, with the highest values recorded under combined high levels of biofertilizer and weed extract application. Grain protein content showed a consistent improvement under both phosphorien inoculation and C. album extract treatments. However, interactions among the studied factors were generally nidgin for most traits. It can be concluded that integration of phosphate-solubilizing bacteria PSB (phosphorien) with foliar application of Chenopodium album aqueous extract is an effective strategy to improve wheat productivity and grain quality under the conditions of clay fertil soils in Egypt.

Keywords: Wheat, Rock phosphate; Phosphate-solubilizing bacteria (PSB), Chenopodium album, Allelopathic Bio fertilizer, Sustainable agriculture.

1. Introduction

Wheat (*Triticum aestivum* L.) is the most widely cultivated cereal crop worldwide and is commonly referred to as the "king of cereals" due to its fundamental role in global food security. It constitutes a staple diet for nearly one-third of the world's population (**Hussain and Shah, 2002**). Global wheat production has shown a continuous upward trend, reaching approximately 793 million metric tons in the 2024/2025 marketing year (**Statista, 2025**). In Egypt, wheat is a strategic crop with exceptionally high consumption rates, where per capita consumption exceeds 180 kg annually, placing the country among the highest consumers worldwide (**Report Linker, 2025**). Despite the expansion in cultivated area and improvements in productivity, the national production remains insufficient to meet the increasing demand driven by population growth. Therefore, enhancing wheat productivity through sustainable and resource-efficient agricultural practices has become an urgent necessity.

Among essential plant nutrients, phosphorus (P) plays a critical role in plant metabolism, including energy transfer, nucleic acid synthesis, root development, and overall plant growth. However, phosphorus availability in soils is often limited due to fixation processes, particularly in calcareous and alkaline soils prevalent in arid and semi-arid regions such as Egypt. The extensive use of chemical phosphorus fertilizers has been the conventional approach to overcome this limitation. Nevertheless, their high cost and associated environmental risks, including soil degradation and water pollution, have raised concerns regarding their long-term sustainability (**Bayrakli, 2022**). Consequently, there is a growing interest in adopting environmentally safe and economically viable alternatives.

Rock phosphate (RP) is considered one of the most promising natural sources of phosphorus due to its abundance, low cost, and eco-friendly nature (**Zapata and Roy, 2004**). However, its direct application in agriculture is restricted by its low solubility, particularly in soils with pH values above 5.5–6.0, which significantly limits phosphorus availability to plants (**Rabari *et al*., 2020**). To improve its agronomic efficiency, biological approaches such as the use of phosphate-solubilizing bacteria (PSB) have been widely explored. These microorganisms possess the ability to convert insoluble forms of phosphorus into plant-available forms through mechanisms such as the production of organic acids, proton extrusion, chelation, and enzymatic hydrolysis (**Khan *et al*., 2016; Behera *et al*., 2017**). Inoculation with PSB has been reported to enhance phosphorus availability from both soil reserves and rock phosphate, leading to improved plant growth, nutrient uptake, and yield (**Kaur and Reddy, 2015; Singh and Reddy, 2022; Gomaa, 2024-a; Ahmed *et al.*2025**).

In Egypt, *Bacillus megaterium* var. *phosphaticum*, commercially known as Phosphorien, is widely used as an effective phosphorus bio fertilizer. Previous studies have demonstrated that the combined application of RP with PSB and organic amendments significantly enhances wheat growth, yield components, and phosphorus uptake compared to the sole application of RP (**Abbasi *et al*., 2013; Wahid *et al*., 2015; Sumreen *et al*., 2022**). This integrated nutrient management approach not only improves phosphorus use efficiency but also contributes to reducing reliance on chemical fertilizers, lowering production costs, and mitigating environmental pollution.

In addition to nutrient limitations, weed infestation represents a major biotic constraint affecting wheat productivity. Weeds compete aggressively with wheat plants for essential resources such as water, nutrients, and light, resulting in significant yield reductions estimated at 17–25% annually (**Jabeen *et al*., 2013; Siyar *et al*., 2017**). Beyond direct competition, many weed species exert allelopathic effects through the release of secondary metabolites that influence crop growth and development (**Ming, 1999; Roy *et al*., 2006; Gomaa, 2024-b**). Recently, the concept of utilizing aqueous extracts of weeds has emerged as a novel and eco-friendly approach, not only for weed management but also as natural plant biostimulants that can enhance physiological processes, nutrient uptake, and stress tolerance (**Iqbal *et al*., 2020; Gomaa, 2021**).

Chenopodium album L. (lamb's quarters), a prevalent weed in wheat fields, is known for its strong allelopathic potential due to its richness in bioactive compounds such as phenolics, flavonoids, and saponins (**Farooq *et al*., 2011; Javaid *et al*., 2018; Gomaa, 2021**). The effects of its aqueous extracts on wheat plants have been reported to be concentration-dependent. Lower concentrations have been shown to stimulate plant growth, improve yield attributes, and enhance grain quality, whereas higher concentrations may inhibit seed germination and suppress plant growth (**Abdul-Majeed *et al*., 2012; Gomaa, 2021**). These findings highlight the potential of weed extracts as dual-function agents that can act either as growth promoters or inhibitors depending on their application concentration.

Despite the considerable body of research addressing the individual roles of rock phosphate, phosphate-solubilizing bacteria, and allelopathic plant extracts, studies investigating their combined and interactive effects under field conditions remain limited. Moreover, there is a lack of comprehensive studies evaluating the integration of mineral, biological, and allelopathic inputs as a unified management strategy for enhancing wheat productivity under Egyptian agro-ecological conditions. Such integration could provide a sustainable approach to optimize nutrient availability, improve plant performance, and reduce environmental impacts.

Therefore, the present study was undertaken to evaluate the main and interactive effects of different levels of rock phosphate, rates of phosphorien biofertilizer, and foliar application of aqueous extract concentrations of *Chenopodium album* on growth, yield, yield components, and grain quality of wheat (*Triticum aestivum* L.) cv. Misr-1 under field conditions.

Materials and Methods

A field experiment was conducted under on-farm conditions at Kafr Al-Naggar Village, Abo Kabir District, Sharkia Governorate, Egypt, during two successive winter seasons of 2020/2021 and 2021/2022. The study aimed to evaluate the main and interactive effects of rock phosphate application, phosphorien biofertilizer rates, and foliar spray of aqueous extract concentrations of *Chenopodium album* on growth, yield, yield attributes, and grain quality of wheat (*Triticum aestivum* L.) cv. Misr-1.

The mechanical and chemical properties of the experimental soil (average of the two seasons) are presented in Table (1), indicating a clay-textured soil with slightly alkaline pH and moderate fertility status. The chemical analysis of irrigation water (Table 2) and the prevailing climatic conditions, including mean temperature and relative humidity during the two growing seasons (Table 3), were also recorded to characterize the experimental environment.

Table 1. Soil mechanical and chemical analyses of the experimental site (mean of the two growing seasons)

Properties	**Mean of the two growing seasons**
Mechanical analysis	
Sand (%)	47.5
Silt (%)	28.4
Clay (%)	24.1
Soil texture	**Clay**
Chemical analysis	
P^H	8.00
Ec ds/m	0.40
Available N (mg/kg)	2200
Available P (mg/kg)	43.52
Available K (mg/kg)	35.98
	Cation(meq/L)
Ca^{++}	77.49
Mg^{++}	7.82

Sources: Central laboratory, Faculty of Agriculture, Zagazig University, Zagazig, Egypt.

Table 2. Irrigation water chemical analysis

Chemical analysis:	**2020-2021**	**2021 -2022**
P^H	7.81	8.20
EC ds/m	0.50	0.54

Sources: Central laboratory, Faculty of Agriculture, Zagazig University, Zagazig, Egypt.

Table 3. Mean temperature and the relative humidity (%) during the winter seasons of 2020-2021 and 2021 - 2022

Month	2020-2021 season				2021-2022 season			
	Temp Max (°C)	Temp Min (°C)	Temp Avg (°C)	RH Mean (%)	Temp Max (°C)	Temp Min (°C)	Temp Avg (°C)	RH Mean (%)
December	20.1	11.9	16.0	60.0	20.1	11.9	16.0	60.0
January	18.3	8.7	13.5	62.0	18.3	8.7	13.5	62.0
February	20.9	10.5	15.7	52.0	20.9	10.5	15.7	52.0
March	23.5	13.3	18.4	50.0	23.5	13.3	18.4	50.0
April	27.1	16.5	21.8	46.0	27.1	16.5	21.8	46.0
May	31.2	20.2	25.7	44.0	31.2	20.2	25.7	44.0

Source: Egyptian Meteorological Authority, Egypt.

The experiment included three factors. The first is rock phosphate (RP), applied at two levels: 0 (control) and 300 kg/fad. The second is the biofertilizer phosphorien, which contains phosphate-solubilizing bacteria (*Bacillus megaterium* var. *phosphaticum*), applied at four inoculation rates: without inoculation (P_1), 300 g/seeds/fad (P_2), 600 g/seeds/fad (P_3), and 900 g /seeds/fad (P_4). The third factor was foliar application of aqueous extract of *Chenopodium album* leaves at three concentrations: 0% (tap water control), 50%, and 100%.

Rock phosphate used in this study was obtained from **Abu-Zaabal Fertilizers and Chemicals Company, Egypt**, and applied at sowing at a rate of 300 kg/fad in the designated treatments. The biofertilizer "phosphorien", produced by the General Organization for Agricultural Equalization Fund (GOAEF), Ministry of Agriculture, Egypt, was applied by mixing the required inoculation rate with sand and broadcasting them uniformly in the soil before the first irrigation.

Fresh plants of *C. album* were collected from naturally growing populations at the Faculty of Agriculture, Zagazig University. Leaves were washed with distilled water, air-dried under shade for 2–3 days, and homogenized at a ratio of 20 g per 100 mL distilled water. The mixture was left for 48 hr at room temperature to allow extraction of bioactive compounds, then filtered through Whatman No. 1 filter paper. The filtrate represented the stock solution (100%), while the 50% concentration was prepared by dilution with distilled water. Foliar spraying was performed using a hand-operated sprayer at 30, 45, and 60 days after sowing (DAS), with the addition of a wetting agent (Kinzo at 100 cm^3/20 L water).

The experiment was arranged in a split–split plot design with three replications. Rock phosphate levels were assigned to the main plots, phosphorien inoculation rates was devoted to subplots, and weed extract concentrations occupied the sub-sub plots. Each experimental unit had an area of 6 m^2 (2 × 3 m).

All agronomic practices were carried out according to the recommendations of the Egyptian Ministry of Agriculture and Land Reclamation. The soil was prepared by plowing, harrowing, and leveling. Wheat grains were sown by broadcasting at a rate of 60 kg/fad on December 1st in both seasons, following maize as a preceding crop. Harvesting was performed on April 25th. Flood irrigation was used throughout the growing season. Potassium fertilizer was applied as potassium sulfate (48% K_2O) at a rate of 50 kg/fad before sowing, while nitrogen fertilizer was applied as ammonium nitrate (33% N) at a rate of 60 kg N/fad in three equal doses at sowing, 21, and 41 days after sowing (DAS).

At 50% heading stage (approximately 85 DAS), samples were collected to measure growth traits. Flag leaf area was determined from ten randomly selected leaves per plot using the formula of leaf length × maximum width × 0.72 (**Lal and Subba Rao, 1951**). Plant height was measured from the soil surface to the tip of the spike (excluding awns). At harvest, one square meter from each plot was sampled to determine number of spikes/m^2, number of grains/spike, and 1000-grain weight. Grain yield, was recorded on a faddan basis (4200 $m^{2)}$. Harvest index was calculated as the ratio of grain yield to biological yield. For grain quality analysis, dried grain samples were ground into fine powder. Nitrogen content was determined according to **AOAC (1980)**, and crude protein percentage was calculated by multiplying nitrogen content by 5.3 (**Weiss, 2000**).

Data from both seasons were subjected to analysis of variance (ANOVA) for split–split plot design using CoStat statistical software. Homogeneity of variance between seasons was tested using Bartlett's test (**Steel *et al.*, 1997**), which indicated no significant differences; therefore, combined analysis over both seasons was performed. Mean comparisons were conducted using the least significant difference (LSD) test at the 5% probability level according to **Duncan (1958)**, and differences among means were indicated using appropriate lettering systems.

3. Results and Discussion

A. Growth Attributes

A.1. Flag Leaf Area (cm²)

Results presented in Table (4) indicate that flag leaf area of wheat at 85 DAS was variably affected by phosphorien inoculation and foliar application of *Chenopodium album* extract, whereas rock phosphate application exhibited insignificant effect.

Rock phosphate (RP) application did not significantly influence flag leaf area in both seasons and the combined analysis. The recorded values ranged from 25.79 cm² under the control (RP_1) to 26.23 cm² under 300 kg RP/fad (RP_2) (pooled analysis results). This lack of response could be attributed to the limited solubility of rock phosphate under alkaline soil conditions (soil pH ≈ 8.0; **Table** 1), which restricts phosphorus availability to plants. These findings are consistent with those reported by **Abbasi *et al.* (2013)**, who observed insignificant effect of sole RP application on wheat growth, and with earlier reports highlighting reduced RP efficiency in high pH soils (**Reddy *et al.*, 2002; Vassilev *et al.*, 2006; Singh and Reddy, 2011**).

Table 4. Efficacy of rock phosphate application (RP), phosphorien inoculation rates (P) and the weed aqueous extract concentrations (W) (*Chenopodium album)* on wheat flag leaf area (cm^2) at 85 DAS in both seasons and the pooled analysis

Main effects and interactions	Flag leaf area (cm^2) at 85 DAS		
	2020-2021	2021-2022	Pooled
Rock phosphate application (RP)			
Check (RP_1)	24.85	26.92	25.79
300 kg/fad (RP_2)	25.33	26.89	26.23
F. test	NS	NS	NS
Phosphorien inoculation rate (P)			
Check (P_1)	23.45	25.41	24.43 b
300 g/fad (P_2)	25.80	26.85	26.33 ab
600g/fad (P_3)	25.56	27.14	26.35 ab
900g/fad (P_4)	25.56	28.25	26.91a
F. test	NS	NS	*
Weed extract concentration (W)			
Check (W_1)	24.69 b	26.11 b	25.40
50 % (W_2)	25.09 ab	27.12 ab	26.11
100 % (W_3)	25.49 a	27.51 a	26.50
F. test	*	*	NS
Interactions			
RP× P	NS	NS	NS
RP× W	NS	NS	NS
P ×W	NS	NS	NS

DAS=Days after sowing *= significant at 5%propapility NS=Not significant

Regarding phosphorien inoculation rates, insignificant differences were observed in both seasons; however, the combined analysis revealed a significant effect. The highest inoculation rate (P_4: 900 g/seeds/fad) produced the largest flag leaf area (26.91 cm^2), compared with the uninoculated control (P_1: 24.43 cm^2). Intermediate values were recorded under P_2 and P_3 treatments. This improvement could be attributed to enhanced phosphate solubilization by phosphate-solubilizing bacteria (PSB), leading to improved nutrient uptake and photosynthetic surface development. Similar findings were reported by **Khattab (2016)**, who demonstrated that PSB application increased flag leaf area of wheat (cultivar-Misr 1).

Foliar application of *C. album* aqueous extract concentrations significantly affected flag leaf area in both seasons, while the meta analysis showed insignificant trend. The highest concentration (W_3: 100%) recorded the greatest values (25.49 and 27.51 cm^2 in the first and the second seasons, respectively), compared with the control (W_1). This stimulatory effect may be attributed to the presence of bioactive compounds such as phenolics and flavonoids, which enhance physiological processes and nutrient uptake. These results are in agreement with **Gomaa (2021)**, who reported a promotive effect of *C. album* extract on wheat flag leaf development.

All interaction effects among RP, phosphorien, and weed extract treatments were insignificant, indicating that each factor acted independently on the flag leaf area under the present experimental conditions.

A.2. Plant Height (cm)

Results in Table (5) reveals that wheat plant height at harvest was slightly influenced by rock phosphate application and phosphorien inoculation rates in the second season only, while insignificant effects were observed in the first season and the consolidated analysis.

Application of rock phosphate at 300 kg/fad resulted in a significant increase in plant height during the second season, with a relative increase of 5.22% compared to the control. However, this effect was not consistent across seasons, as insignificant differences were observed in the first season and the pooled analysis results. This inconsistency may be attributed to the limited solubility and delayed availability of phosphorus from RP under alkaline soil conditions. Similar findings were reported by **Singh and Reddy (2011)** and **Al Mamun *et al.* (2012)**, who indicated that RP had insignificant effect on wheat plant height. In contrast, other studies have reported positive responses when RP was integrated with biological or organic amendments (**Saleem *et al.*, 2013; Chaudhary *et al.*, 2015; Haq *et al.*, 2020**).

Phosphorien inoculation significantly increased plant height in the second season, where the application rate of 300 g/seeds/fad (P_2) recorded the highest value (94.42 cm), representing a 3.28% increase over the uninoculated control. However, differences among higher inoculation rates (P_3 and P_4) were not statistically significant. The promotive effect of PSB may be attributed to enhanced phosphorus availability and improved root development, which in turn supports better vegetative growth. These results are consistent with those reported by **Bashan *et al.* (2004)**, **Egamberdiyeva *et al.* (2004)**, and **Khattab (2016)**, who highlighted the role of PSB in increasing plant height through improved nutrient availability.

Foliar application of *C. album* aqueous extract did not significantly affect plant height in both seasons and the combined analysis. Although slight increases were observed at higher concentrations, these differences were not statistically significant. This may indicate that the allelopathic compounds present in the extract exerted a balanced effect between stimulation and inhibition, depending on concentration. Similar observations were reported by **Abdul-Majeed *et al.* (2012)**, who found that low concentration of *C. album* extract promoted plant growth, whereas higher concentrations reduced plant height due to allelopathic effects of phenolic compounds.

All interactions among the studied factors has insignificant efficacy on wheat plant height, suggesting that the influence of each factor on plant height was independent under the prevailing experimental conditions.

Table 5. Efficacy of phosphate rock application (RP), phosphorien inoculation rates (P) and the weed aqueous extract concentrations (W) (*Chenopodium album*) on wheat plant height (cm) in both seasons and the pooled analysis

Main effects and interactions	Plant height (cm)		
	2020-2021	2021-2022	Pooled
Rock phosphate application (RP)			
Check (RP_1)	87.37	90.93 b	89.15
300 kg/fad (RP_2)	86.56	95.68 a	91.12
F. test	NS	*	NS
Phosphorien inoculation rate (P)			
Check (P_1)	86.10	91.42 b	88.76
300 g/fad (P_2)	87.16	94.42 a	90.79
600g/fad (P_3)	89.12	92.76 ab	90.94
900g/fad (P_4)	87.30	92.70 ab	90.00
F.test	NS	*	NS
Weed extract concentration (W)			
Check (W_1)	86.97	90.51	88.74
50 % (W_2)	86.93	94.17	90.55
100 % (W_3)	89.21	92.85	91.03
F test	NS	NS	NS
Interactions			
RP * P	NS	NS	NS
RP* W	NS	NS	NS
P * W	NS	NS	NS

DAS=Days after sowing *= significant at 5%propapility NS=Not significant

B. Yield and yield attributes

B.1. Number of spikes /m²

Results presented in Table (6) display that the number of spikes per square meter was significantly affected by rock phosphate application, phosphorien inoculation rates, and *Chenopodium album* aqueous extract concentrations, with a significant interaction observed between rock phosphate (RP) and phosphorien (P) treatments.

Application of rock phosphate at 300 kg/fad resulted in a significant increase in spike number/m^2 in the first season and the pooled analysis, with a pooled mean of 464.37 spikes m^2 compared with 459.84 spikes m^{-2} in the control. This improvement may be attributed to the role of phosphorus in enhancing tillering capacity and spike formation. Phosphorus is known to stimulate early root development and tiller initiation, which ultimately determines the number of productive spikes per unit area. Similar trends were reported by **Sepat and Rai (2013)** and **Chaudhary *et al.* (2015)**, who emphasized the positive role of rock phosphate in improving wheat stand density.

Phosphorien inoculation had a highly significant effect on spike number/m^2 in both seasons and the combined analysis. The highest value was recorded under each of P_3 (600 g/seeds/fad) and P_4 (900 g/seeds/fad), with pooled means of 472.00 and 470.66 spikes m^2, respectively, compared with 450.00 spikes m^{-2} in the control. The promotive effect of PSB may be attributed to improved phosphorus solubilization and enhanced nutrient uptake efficiency, leading to better tiller survival and spike development. These findings are in agreement with **Afzal *et al.* (2005)**, **Khattab (2016)**, **Hasan *et al.* (2021)**, **and Gomaa (2024-a)**, who reported increased spike density under PSB inoculation.

Foliar application of *C. album* extract concentrations significantly increased spike number/m^2, with the highest concentration (W_3) recording the maximum value (473.00 spikes m² in pooled analysis result), representing a 4.12% increase over the control. This stimulatory effect may be related to the presence of bioactive compounds that enhance physiological activity and reduce internal competition stress. Similar observations were reported by **Gomaa (2021)**.

Table 6. Efficacy of phosphate rock application (RP), phosphorien inoculation rates (P) and the weed aqueous extract concentrations (W) (*Chenopodium album*) on number of wheat spikes/m^2 in both seasons and the pooled analysis

Main effects and interactions	Number of spikes/m^2		
	2020-2021	2021-2022	Pooled
Rock phosphate application (RP)			
Check (R_1)	446.59 b	473.08	459.84 b
300 kg/fad (R_2)	454.52 a	474.21	464.37 a
F test	*	NS	*
Phosphorien inoculation rate (P)			
Check (P_1)	441.00 b	459.00 c	450.00 b
300 g/fad (P_2)	433.20 b	478.80 b	456.00 b
600g/fad (P_3)	448.40 ab	495.60 a	472.00 a
900g/fad (P_4)	461.25 a	480.07 b	470.66 a
F test	*	*	*
Weed extract concentration (W)			
Check (W_1)	445.20 b	463.38 b	454.29 b
50 % (W_2)	450.18 ab	468.56 ab	459.37 ab
100 % (W_3)	463.54 a	482.46 a	473.00 a
F test	*	*	*
Interactions			
RP × P	NS	NS	NS
RP × W	NS	NS	NS
P × W	NS	NS	NS

DAS=Days after sowing *= significant at 5%propapility NS=Not significant

The spike number/m^2 was not affected by the interplay between the main factor under study.

B.2. Number of grains per spike

Results in Table (7) indicate that all studied factors significantly influenced grain number per spike, with clear positive responses to rock phosphate application, phosphorien inoculation rates, and *C. album* extract concentrations.

Rock phosphate application operatively increased grain number per spike, with a pooled mean of 52.10 grains compared with 46.80 grains in the control. The improvement (11.32%) reflects the essential role of phosphorus in reproductive development and spike fertility. These findings are consistent with **Sepat and Rai (2013) and Chaudhary *et al.* (2015)**, who reported similar improvements under RP fertilization.

Phosphorien inoculation rates showed a strong positive effect, particularly at 900 g/seeds/fad (P_4), which recorded the highest grain number (56.1 grains/spike). The increase ranged from 20.14% to 34.53% over the control (pooled analysis results), indicating the tremendous role of PSB in improving phosphorus availability during the reproductive stage, thereby enhancing floret fertility and grain set. Similar trends were reported by **Attia and Abd El Salam (2016), Alam *et al.* (2022), and Gomaa (2024-a)**.

Foliar spraying with *C. album* aqueous extract significantly improved grain number, with W_2 and W_3 concentrations, grain number increased by 37.60% and 42.04%, respectively, compared to the control (the meta-analysis results). This may be attributed to the stimulatory effect of bioactive compounds enhancing assimilate production and translocation to developing grains. Comparable findings were reported by **Chilwal *et al.* (2017),** while **Gomaa (2021)** noted a concentration-dependent response.

No significant interactions were detected among the main factors, indicating independent effects on grain number per spike.

Table 7. Efficacy of phosphate rock application (RP), phosphorien inoculation rates (P) and the weed aqueous extract concentrations (W) (*Chenopodium album*) on wheat number of grains/spike in both seasons and the pooled analysis

Main effects and interactions	Number of grains /spike		
	2020-2021	2021-2022	Pooled
Rock phosphate application (RP)			
Check (R_1)	46.90 b	46.70 b	46.80 b
300 kg/fad (R_2)	53.80 a	50.60 a	52.10 a
F. test	*	*	*
Phosphorien inoculation rate(P)			
Check (P_1)	42.1 c	41.3 d	41.7 c
300 g/fad (P_2)	49.0 b	51.1 b	50.1 b
600g/fad (P_3)	50.1 b	49.1 c	49.6 b
900g/fad (P_4)	55.0 a	57.2 a	56.1 a
F test	*	*	*
Weed extract concentration (W)			
Check (W_1)	38.3 c	38.3 c	38.3 c
50 % (W_2)	51.7 b	53.7 b	52.7 b
100 % (W_3)	53.8 a	54.9 a	54.4 a
F test	*	*	*
Interactions			
RP × P	NS	NS	NS
RP× W	NS	NS	NS
P × W	NS	NS	NS

DAS=Days after sowing *= significant at 5%propapility NS=Not significant

B.3. 1000-grain weight

Results in Table (8) reveals that 1000-grain weight was operatively influenced by all studied factors, with significant interaction observed between rock phosphate and *C. album* extract.

Rock phosphate application slightly reduced 1000-grain weight, although the difference was statistically significant. The reduction may be attributed to a dilution effect caused by increased sink number (spikes and grains), leading to a redistribution of assimilates. Similar results were reported by **Al Mamun *et al.* (2012)**, while contrast findings were reported under integrated nutrient management systems (**Abbasi *et al.*, 2013; Haq *et al.*, 2020**).

Phosphorien inoculation rates significantly improved grain weight, particularly at 600 and 900 g/seeds/fad, with pooled increases of 5.98% and 2.90%, respectively, compared to the control. This improvement is attributed to enhanced phosphorus uptake during grain filling, which supports starch accumulation and grain filling duration. These results agree with **Saleem *et al.* (2013), Khattab (2016), and Gomaa (2024-a).**

Foliar application of *C. album* extract concentrations significantly increased 1000-grain weight, with W_2 and W_3 treatments recording increases of 35.13% and 37.43%, respectively, over the control (pooled analysis). This may be due to improved photosynthetic efficiency and nutrient mobilization during grain filling.

A significant interaction between rock phosphate (RP) and *C. album* extract concentrations(W) was observed (Table 9), where the uppermost grain weight was recorded under $RP_2 \times W_3$ (43.56 g), while the lowermost one was under $RP_1 \times W_1$ (32.00 g). This indicates that foliar bio stimulants can partially compensate for variations in soil phosphorus availability by enhancing assimilate partitioning to grains.

Table 8. Efficacy of phosphate rock application (RP), phosphorien inoculation rates (P) and the weed aqueous extract concentrations (W) (*Chenopodium album*) on 1000 grain weight (g) of wheat in both seasons and the pooled analysis

Main effects and interactions	1000 -grain weight (g)		
	2020-2021	2021-2022	Pooled
Rock phosphate application (RP)			
Check (R_1)	37.75 a	41.73 a	39.74 a
300 kg/fad (R_2)	37.39 b	41.33 b	39.36 b
F test	*	*	*
Phosphorien inoculation rate (P)			
Check (P_1)	37.08 b	40.18 ab	38.63 b
300 g/fad (P_2)	38.17 b	39.73 b	38.95 b
600g/fad (P_3)	39.71 a	42.17 a	40.94 a
900g/fad (P_4)	38.56 a	40.94 ab	39.75 a
F test	*	*	*
Weed extract concentration (W)			
Check (W_1)	30.58 b	33.12 b	31.85 b
50 % (W_2)	41.75 a	44.33 a	43.04 a
100 % (W_3)	42.02 a	45.52 a	43.77 a
F test	*	*	*
Interactions			
RP × P	NS	NS	NS
RP × W	*	*	*
P × W	NS	NS	NS

DAS=Days after sowing *= significant at 5%propapility NS=Not significant

Table 9. 1000 grain weight of wheat as affected by the interaction between rock phosphate application (RP) and *Chenopodium album* aqueous extract concentration (W)

C. album weed aqueous extract concentration (W)	Rock phosphate application (RP)	
	Check (RP_1)	300kg (RP_2)
W_1 (check)	A 32.00 b	A 31.70 b
W_2 (50%)	A 43.25 a	A 42.83 a
W_3(100%)	A 43.98 a	A 43.56 a

B-4- Grain yield (kg/fad)

Results presented in Table (10) illustrate the effect of rock phosphate application (RP), phosphorien inoculation rates (P), and foliar spraying with *Chenopodium album* aqueous extract (W) on grain yield (kg/fad) of wheat cultivar Misr-1 in both seasons and their combined analysis.

Application of rock phosphate at 300 kg/fad (RP_2) showed a consistent numerical increase in grain yield compared with the control (RP_1) across both seasons and in the pooled analysis; however, these increases did not reach statistical significance. This slight improvement in yield may be attributed to the indirect positive effects of rock phosphate on yield components, including number of grains per spike (Table 7), and spikes per m² (Table 6). In this context, adequate phosphorus availability is known to enhance tillering and reproductive development, which ultimately contributes to yield formation.

Table 10. Efficacy of phosphate rock application (RP), phosphorien inoculation rates (P) and the weed aqueous extract concentrations (W) (*Chenopodium album*) on wheat grain yield in both seasons and the pooled analysis

Main effects and interactions	Grain yield (kg/fad)		
	2020-2021	2021-2022	Pooled
Rock phosphate application (RP)			
Check (R_1)	2704	2903	2811
300 kg/fad (R_2)	2843	3093	2985
F test	NS	NS	NS
Phosphorien inoculation rate (P)			
Check (P_1)	2520 b	2650 b	2598 b
300 g/fad (P_2)	2638 b	2900 b	2777 b
600g/fad (P_3)	2970 a	3261 a	3126 a
900g/fad (P_4)	2968 a	3189 a	3092 a
F test	*	*	*
Weed extract concentration (W)			
Check (W_1)	2632 c	2911 b	2782 b
50 % (W_2)	2761 b	3013 ab	2897 ab
100 % (W_3)	2938 a	3076 a	3017 a
F test	*	*	*
Interactions			
RP × P	NS	NS	NS
RP × W	*	*	*
P × W	NS	NS	NS

DAS=Days after sowing *= significant at 5%propapility NS=Not significant

The role of rock phosphate in improving wheat productivity has been previously reported when used alone or in combination with phosphate-solubilizing bacteria (PSB), as documented by several researchers (*e.g.*, **Abbasi *et al.*, 2013; Saleem *et al.*, 2013; Chaudhary *et al.*, 2015; Haq *et al.*, 2020**), although responses often depend on soil pH and phosphorus availability.

Allusive to phosphorien inoculation rates, results clearly indicated a significant response in both seasons and the consolidated analysis. Inoculation at higher rates (P_3: 600 g and P_4: 900 g/seeds/fad) significantly increased grain yield compared with the control (P_1) and the lowest rate (P_2). Based on pooled analysis results, relative increases reached 20.32% and 19.01% for P_3 and P_4, respectively, compared with the uninoculated control.

This improvement in grain yield is mainly attributed to the positive influence of phosphorien on most yield attributes such as flag leaf area (Table 4), number of grains per spike (Table 7), number of spikes per m² (Table

6), and 1000-grain weight (Table 8). The observed response can be explained by the ability of phosphate-solubilizing bacteria to convert insoluble phosphorus into plant-available forms through organic acid production and rhizosphere modification, thereby enhancing nutrient uptake and crop productivity.

Concerning foliar application of *Chenopodium album* aqueous extract concentrations, results declared a clear positive effect on grain yield, particularly at the highest concentration (W_3: 100%), which significantly outbrave the control (W_1) in both seasons and the pooled analysis. The overall increase reached 8.45% under W_3 compared with W_1, while W_2 (50%) showed an intermediate response.

The superiority of treated plants with the *C. album* aqueous extract may be attributed to the improvements in yield components such as flag leaf area, spike length, spike density, grain weight per spike, number of grains per spike, spikes per m², and 1000-grain weight, indicating a general enhancement of plant physiological efficiency under weed extract application.

Interaction analysis (Table 11) revealed that the combined application of rock phosphate (RP_2) and 100% *C. album* extract (W_3) produced the highest grain yield (3107kg/fad), while the lowest yield (2698.49 kg/fad) was recorded under the control interaction ($RP_1 \times W_1$), confirming the synergistic effect between phosphorus supply and foliar bio-stimulant application.

Table 11. Wheat grain yield as affected by the interaction between rock phosphate application (RP) and *Chenopodium album* aqueous extract concentrations (W)

C. album weed aqueous extract concentration (W)	Rock phosphate application (RP)	
	Check (RP_1)	300kg (RP_2)
W_1(check)	B 2698.49 c	A 2865.50 c
W_2 (50%)	B 2810.03 b	A 2983.96 b
W_3(100%)	B 2926.43 a	A 3107.56 a

B-5- Harvest index (%)

Results of harvest index (%) as affected by rock phosphate application, phosphorien inoculation rates, and *Chenopodium album* aqueous extract concentrations are outlined in Table (12).

Rock phosphate application treatments exhibited insignificant effect on harvest index in both seasons and the meta-analysis, indicating that the slight increases in grain and straw yields were proportionally balanced, resulting in a stable partitioning between economic and biological yields.

In contrast, phosphorien inoculation rates operatively affected harvest index in both seasons and in the pooled analysis. All inoculated treatments (P_2, P_3, and P_4) generally surpassed the uninoculated control (P_1), with minor differences among inoculation rates. This response reflects the overall improvement in assimilate production and its partitioning towards grain formation, as supported by improvements in yield components and grain yield (Table 10). Similar findings have been reported for phosphate-solubilizing bacteria and mycorrhizal associations enhancing nutrient uptake and biomass partitioning efficiency.

Foliar application of *Chenopodium album* aqueous extract also significantly influenced harvest index. The highest value (49.56%) was recorded under 50% concentration (W_2), which surpassed both W_1 and W_3 treatments (pooled analysis results). This indicates that moderate concentration may optimize assimilate distribution between grain and straw, possibly by improving physiological balance rather than excessive vegetative stimulation.

Interaction effects among the studied factors were generally insignificant, indicating that the main effects were largely independent in their influence on harvest index.

Table 12. Efficacy of phosphate rock application (RP), phosphorien inoculation rates (P) and the weed aqueous extract concentrations (W) (*Chenopodium album*) on harvest index (%) of wheat in both seasons and the pooled analysis

Main effects and interactions	Harvest index (%)		
	2020-2021	2021-2022	Pooled
Rock phosphate application (RP)			
Check (R_1)	48.28	47.73	48.01
300 kg/fad (R_2)	49.11	49.09	49.10
F test	NS	NS	NS
Phosphorien inoculation rate (P)			
Check (P_1)	47.62 c	46.95 c	47.29 b
300 g/fad (P_2)	49.55 a	48.08 bc	48.82 a
600g/fad (P_3)	48.21 bc	50.10 a	49.16 a
900g/fad (P_4)	49.42 ab	48.62 a	49.02 a
F test	*	*	*
Weed extract concentration (W)			
Check (W_1)	48.31 b	47.26 b	47.79 b
50 % (W_2)	49.86 a	49.26 a	49.56 a
100 % (W_3)	47.97 b	48.78 a	48.38 b
F test	*	*	*
Interactions			
RP × P	NS	NS	NS
RP × W	NS	NS	NS
P × W	NS	*	NS

DAS=Days after sowing *= significant at 5%propapility NS=Not significant

C. Grain quality

Grain protein content (%)

Results compiled in Table (13) points to the effects of rock phosphate application (RP), phosphorien inoculation rates (P), and foliar spraying with *Chenopodium album* aqueous extract (W) on grain protein content (%) of wheat cultivar Misr-1 in both growing seasons and their meta-analysis.

Application of rock phosphate showed insignificant effect on grain protein content in either season or in the pooled analysis. Both treatments (RP_1 and RP_2) resulted in comparable protein percentages, indicating that under the prevailing soil conditions (alkaline soil with relatively adequate available phosphorus), rock phosphate application had limited influence on grain protein accumulation. This agrees with the general scarcity of studies addressing the direct effect of rock phosphate on wheat grain quality traits.

In contrast, phosphorien inoculation rates significantly affected grain protein content in both seasons and in the combined analysis. All inoculation treatments improved protein content compared with the uninoculated control, with the highest response recorded under P_4 (900 g/seeds/fad). Based on pooled results, P_4 increased grain protein content by 21.22% comparably with the control (P_1).

This improvement can be attributed to the role of phosphate-solubilizing bacteria (PSB) in enhancing phosphorus availability in the rhizosphere, which subsequently promotes nitrogen uptake, assimilation, and protein synthesis in wheat grains. Similar responses have been previously reported by several authors (*e.g.*, **Ozturk and Caglar, 2003; Badr *et al.*, 2009; Radwan *et al.*, 2013; Khattab, 2016; Gomaa, 2024-a**), confirming the positive association between biological phosphorus mobilization and grain protein enrichment.

Regarding foliar application of *Chenopodium album* aqueous extract concentrations, results displayed a consistent and significant increase in grain protein content in both seasons. Both concentrations (W_2: 50% and W_3: 100%) significantly outclassed the control (W_1), with the highest value recorded under W_3. Based on pooled analysis, protein content increased by 9.04% and 13.79% under W_2 and W_3, respectively, comparatively with the control.

The enhancement in grain protein content under weed extract application may be associated with its stimulatory effect on plant physiological processes, including improved photosynthetic efficiency and nutrient uptake, which is reflected in better assimilate accumulation and nitrogen metabolism. This trend was also consistent with the improvements observed in several yield-related traits such as flag leaf area (Table 4), number of grains per spike (Table 7), spikes per m² (Table 6), 1000-grain weight (Table 8), grain yield (Table 10), and harvest index (Table 12), indicating a general enhancement of plant performance under foliar application of *C. album* aqueous extract.

Interaction effects among the studied factors (RP × P, RP × W, and P × W) were not significant in both seasons and the combined analysis, indicating that the main effects acted independently on grain protein content without synergistic or antagonistic interactions.

Table 13. Efficacy of phosphate rock application (RP), phosphorien inoculation rates (P) and the weed aqueous extract concentrations (W) (*Chenopodium album*) on grain protein content (%) of wheat in both seasons and the pooled analysis

Main effects and interactions	Grain protein content (%)		
	2020-2021	2021-2022	Pooled
Rock phosphate application (RP)			
Check (R_1)	11.28	12.20	11.84
300 kg/fad (R_2)	11.53	12.74	12.13
F test	NS	NS	NS
Phosphorien inoculation rate (P)			
Check (P_1)	10.21 c	11.73 b	11.17 b
300 g/fad (P_2)	11.57 ab	12.05 b	11.81 b
600g/fad (P_3)	11.13 ab	11.81 b	11.47 b
900g/fad (P_4)	13.00 a	14.04 a	13.54 a
F test	*	*	*
Weed extract concentration (W)			
Check (W_1)	9.95 b	11.39 b	11.17 b
50 % (W_2)	11.80 a	12.56 a	12.18 a
100 % (W_3)	12.73 a	13.09 a	12.71 a
F test	*	*	*
Interactions			
RP × P	NS	NS	NS
RP × W	NS	NS	NS
P × W	NS	NS	NS

DAS=Days after sowing *= significant at 5%propapility NS=Not significant

4. Conclusion

The present study was conducted to evaluate the influence of rock phosphate application, phosphorien inoculation rates (phosphate-solubilizing bacteria), and foliar application of *Chenopodium album* aqueous extract concentrations on the growth, yield attributes, yield, and grain quality of wheat (cv. Misr-1) under field conditions in Sharkia Governorate, Egypt during two consecutive winter seasons (2020/2021 and 2021/2022).

Overall, the results revealed that rock phosphate application at 300 kg/fad declared a generally positive but mostly insignificant effects on most studied traits, indicating limited availability of phosphorus under the prevailing alkaline soil conditions. In contrast, phosphorien inoculation rates significantly improved several growth and yield parameters, particularly at higher rates (600 and 900 g/seeds/fad), reflecting the effective role of phosphate-solubilizing bacteria (PSB)in enhancing phosphorus availability and nutrient uptake.

Foliar spraying with *Chenopodium album* aqueous extract, especially at 100% concentration, consistently improved most agronomic traits, yield components, grain yield, and grain quality compared with the control. This improvement may be attributed to the presence of biologically active compounds that enhanced plant metabolic activity and nutrient efficiency.

Interactions among treatments were generally insignificant for most traits, indicating that each factor mainly acted independently, except for few cases where combined effects were evident.

It can be concluded that integrating biofertilizer phosphorien with foliar application of *Chenopodium album* extract represents a promising strategy to enhance wheat productivity and grain quality under similar soil and environmental conditions, while rock phosphate alone showed limited effectiveness under alkaline soil conditions.

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