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The Contribution of Agronomic Management to Sustainably Intensify Egypt's Wheat Production

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Abstract: In Egypt, recent shortfalls in the wheat supply from Russia and Ukraine have necessitated substantial increases in domestic production. As agricultural practices influence the yield of bread wheat, we assessed current production strategies in the wheat-based systems of Egypt and investigated their effects on wheat productivity in four study areas in the Nile Delta. We used a multi-stage random sampling technique to select 246 wheat-producing farmers and applied structured questionnaires to assess farming practices and crop performance attributes. Data were analyzed by using descriptive statistics, analysis of variances, and multiple regression models. Wheat farmers were on average 56 years old with about 30 years of farming experience. Land holdings were rather small, with an average of 1.05 hectares and a mean wheat yield of 6.4 metric tons (t)/hectare (ha). Farmers devote <20% of their cropland area to wheat. Of the large observed variation in wheat yield (4.2–8.5 t/ha), 59% was explained by differences in applied cropping practices in the multiple regression model. The application of mineral fertilizers was mostly inappropriate and unbalanced, with an overuse of nitrogen and phosphorus, the complete absence of potassium and micronutrient fertilizers, and insufficient rates of applied organic amendments. The type of the preceding summer crop and the irrigation frequency were found to be the most influencing factors, explaining 7.5% and 38% of the variation in wheat yields. The majority of farmers with low wheat yields irrigated their crops twice per season, while only 7% of high-yielding farmers applied the recommended irrigation frequency of >5 times per season. Most farmers had poor knowledge of modern agronomic practices and inadequate access to information. To enhance domestic production in Egypt, there is a need for fiscal incentives, permitting or stimulating wheat-producing farmers to devote larger shares of their cropland to wheat cultivation. In addition, policies must enable wheat producers to improve their productivity by implementing adequate and sustainable agricultural practices such as crop rotations, balanced mineral nutrient supply, and the use of organic amendments. However, the most important factors are interventions and technologies that improve provision and increase the use efficiency of irrigation water.

Keywords: agronomic practices; fertilizers; food security; irrigation; *Triticum aestivum*

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1. Introduction

Given that Egypt is an agricultural country, 53% of the population lives in rural areas, with livelihood directly or indirectly depending on agricultural activities. About 27% of the population is employed in agriculture, a sector contributing nearly 15% of the national income [1]. However, 97% of Egyptian land is desert. Out of the total land area of about 100 million hectares (ha), Egypt has a cultivated land area of only 3.6 million hectares (ha), of which, approximately 2.7 million hectares (ha) are concentrated in and around the Nile Delta [2]. There, crop farming is practiced on both the "old land" and the "new land". The "old land" is located along the Nile River and in the Delta region, extending from Giza in the South to El Manzala and Rashid in the North, covering about one million ha of arable land [2]. The area is characterized by heavy alluvial clay soils with high organic carbon content and a high water-holding capacity. Water supply to crops relies mainly on surface gravity irrigation. The "new land", on the other hand, has been reclaimed recently from the desert. Located west and east of the Delta and covering 0.88 million hectares (ha), the new land is characterized by sandy soils with low water-holding capacity and low soil fertility. Water for crops is provided by pressurized irrigation systems (sprinklers and pivot irrigation) [3].

Bread wheat (*Triticum aestivum* L.) is the most important crop in Egypt, occupying 1.5 million hectares (ha) [4] and representing nearly half of the total cultivated area during the winter season [5]. In addition, Egyptians derive 1/3 of their daily caloric intake and 45% of their protein intake from wheat-based food, mainly in the form of *baladi* bread. Egypt consumes the equivalent of 20 million metric tons (t) of wheat per year, and less than half of this amount is met from domestic production, the remaining share being covered by imports. In 2021, Russia and Ukraine contributed 85% of the total wheat imports to Egypt (60–66% from Russia and 20–25% from Ukraine) [6]. Wheat prices in Egypt increased by 100% between June 2021 and April 2022 [6], with the largest increases occurring at the beginning of the Russia–Ukraine war in February 2022 and contributing to the national inflation record high of 20% in March 2022 [7]. With recently soaring wheat prices on international markets, the annual cost for wheat imports into Egypt is expected to further increase in 2023, thus creating a significant burden on the Egyptian economy.

To mitigate the risk of bread shortages and potential social unrest resulting from abrupt increases in the price of bread, Egypt must take steps to reduce its reliance on imports of wheat from Russia and Ukraine. This can be achieved through the exploration of alternative sources of international wheat and, more importantly, by enhancing domestic wheat production [8]. The government of Egypt has already outlined the vision of increasing domestic wheat production in the "Egypt Sustainable Development Strategy Towards 2030" in 2014. The document emphasized the government's aspiration to attain 74% wheat self-sufficiency by 2017. However, self-sufficiency in 2017 reached only 43%.

The increasing gap between domestic wheat production and consumption has been mainly the result of drivers outside of the sphere of agricultural production. Thus, the rapid population growth rate, policies to subsidize the price of bread while withdrawing subsidies for farm inputs, late declarations of prices by the government, and changing climate conditions acted as external pressures, increasing wheat demand while disincentivizing domestic production. Agriculture system-immanent responses of small-scale wheat producers included devoting larger shares of the wheat harvest to home consumption and for feeding animals instead of selling it to the government for filling the storage silos. Additionally, the low productivity of domestically produced wheat incentivizes farmers to reduce the area cultivated with wheat and to substitute wheat in the crop portfolio with other, more economically competitive crops, such as clover and broad beans [6].

In the past, Egypt compensated for low domestic production by increasing wheat imports; however, this compensation was at the cost of declining food self-sufficiency. With recent disruptions in wheat supply from Russia and Ukraine, and skyrocketing prices for wheat and agrochemicals on international markets, there is an urgent need to strengthen domestic production by increasing cultivation and intensifying production practices. The latter entails balancing the application of external inputs and enhancing the efficiency of scarce water resources. Considering the large gap between potential wheat yields of over 10 t/ha [9] and farmers' actual yields of about 6 t/ha [5], it is apparent that production increases are achievable. The focal target area for such production gains is the Nile Delta, with its fertile soils and adequate access to irrigation water. This is particularly the case for El Beheira Governorate, where 65% of the wheat in Egypt is currently produced [10].

There is little knowledge regarding the status quo of current production strategies and of the performance attributes of wheat-based systems in relation to the on-farm resource endowment of wheat producers (availability of land, labor, and capital). We surmise that farmers' adaptive capacity to respond in a timely manner to changing demands is related to their access to modern technologies and extension services, as well as to the availability and use of human capital [11].

The main objective of this study was to investigate current production practices and identify key constraints affecting wheat productivity in smallholder farms in El Beheira Governorate, which is located in the Nile Delta of Egypt. We combined structured interviews, field observations, and transect walks to collect data from 246 smallholder wheat farms in the study area. Specifically, we aimed to:

(1) identify the current production practices used by smallholder wheat farmers in the study area, including cultivation methods, and water management;
(2) identify the key constraints affecting wheat productivity in smallholder farms, both as perceived by farmers and as observed by researchers, including issues related to soil management, access to inputs and markets, and labor availability;
(3) relate crop performance attributes, such as yield, to the identified constraints affecting wheat productivity;
(4) outline the necessary actions to develop yield-gap-reducing production strategies that can be targeted to smallholder wheat farms in the study area and to guide policymakers and stakeholders in developing targeted interventions and policies that promote sustainable wheat production in Egypt.

Overall, the goal of this study was to provide insights into the current state of wheat production in smallholder farms in El Beheira Governorate and to provide recommendations for improving productivity and sustainability in this important sector.

2. Methods

2.1. Description of the Study Area

Approximately 57% of the land used for wheat cultivation in Egypt is located in the Nile Delta [12]. We selected El Beheira Governorate in the North-West of the Nile Delta (30°36′36″ N, 30°25′48″ E) as the key study area since it is the wheat basket of Egypt, where millions of smallholders cultivate wheat with production methods similar to those in other wheat-growing areas in Egypt. El Beheira Governorate covers 9826 km^2 west of the Rosetta branch of the river Nile. It is densely populated with approximately 7 million people, of which more than 70% work in agriculture. Four highways connect El Beheira to the central markets of Cairo and Alexandria. It consists of 13 centers, 14 cities, 84 rural municipalities, and 407 villages [8].

While representing only 15% of the total agricultural land area of Egypt [13], El Beheira Governorate produces 60–65% of the total wheat of the country. Wheat is grown in rotation with irrigated summer crops on relatively small land holdings in the peri-urban fringes of the "old land", and with pivot and overhead sprinkler irrigation in fallow rotation systems on large land holdings in rural areas of the "new land" [14]. Within El Beheira Governorate, four municipal divisions were selected as the main study areas, based on differences in water availability, market access, and soil type. They comprised (1) Al Mahmoudiya Division, consisting of 14 villages located on the Rosetta branch of the Nile (rural–moist scenario); (2) Kafr El Dawar Division, consisting of 31 villages located along major highways with good market access (urban–moist scenario); (3) Abu El Matamir Division, consisting of 24 villages located on the desert margin (rural–dry scenario); and (4) El Nubariyah Division, representing the cultivated desert (urban–dry scenario) (Figure 1).

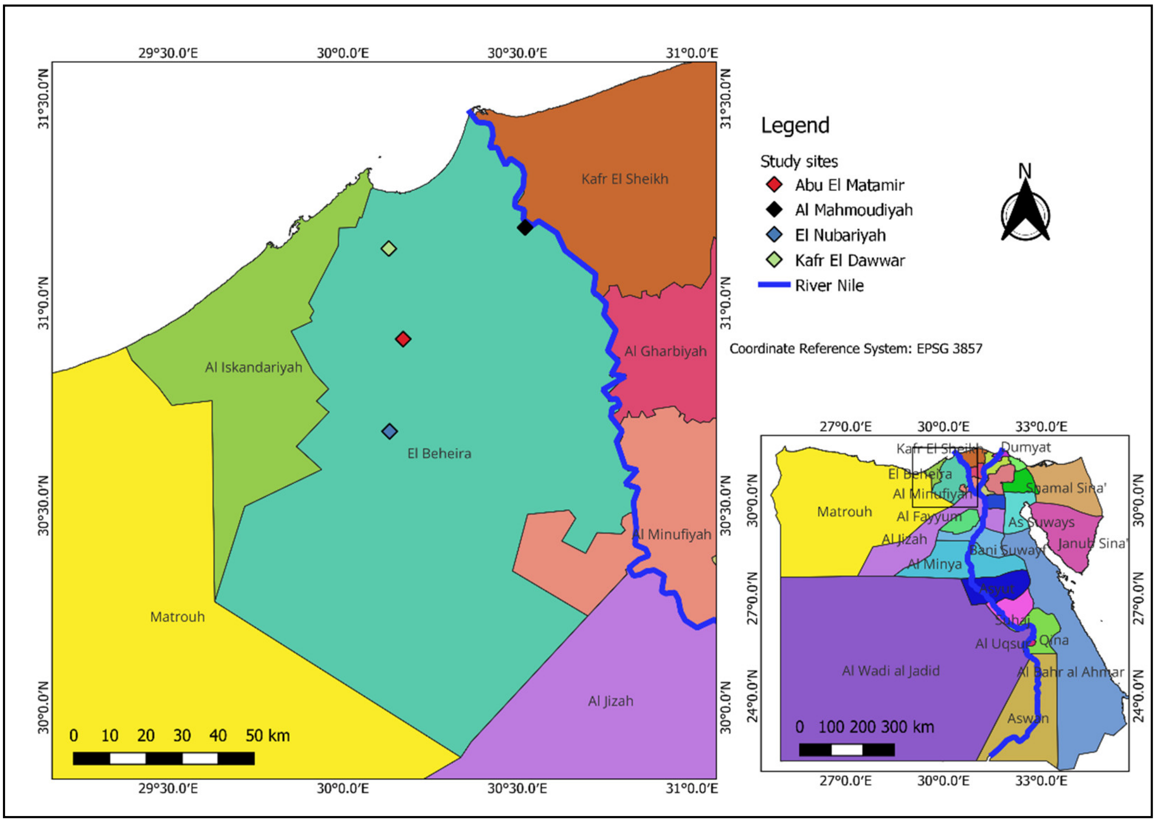

Figure 1. Study locations (municipal divisions) within El Beheira Governate in Northern Egypt.

2.2. Data Collection

We identified 246 wheat growers by random selection from official documents from the official units of the Ministry of Agriculture and Land Reclamation in each study area (MALR), listing all wheat-growing households of each village. The number of wheat growers selected in each municipal division was proportional to the respective farmer populations. The number of participants was deemed sufficient to achieve the desired level of statistical significance and precision (sufficient to obtain a 95% confidence interval with a margin of error of ±5%) while also ensuring the feasibility of data collection within the timeline and resources of the study.

We systematically characterized and categorized prevailing production practices, the resource endowment of households, and wheat performance attributes during the wheat-cropping season of 2020/2021. We interviewed wheat-producing farmers by using structured questionnaires, which were divided into two sections: (1) farmer attributes and resource endowment, and (2) agronomic practices. The questionnaires were pre-tested with 25 farmers in all 4 study areas. The survey part on agronomic practices included questions on crop rotations, seed sources, soil tillage, crop establishment, mineral and organic fertilizer use, number of irrigation events applied, weed and pest control strategies, harvesting methods, and produce uses (sale vs. home consumption).

2.3. Data Analysis

Descriptive statistics analyzed the primary data. Frequency counts, percentages, and means described the socio-economic characteristics of the survey respondents. We used two-way ANOVA to test for differences in agronomic practices and wheat yields.

We tested the response variable "Wheat yield" against 14 predictor variables to identify the main yield-affecting agronomic practices via multiple linear models [15]. The potentially yield-affecting variables comprised location and soil type; the preceding crop rotation; tillage method (manual, animal, mechanical) and tillage depth; seed source (market vs.

self-grown) and seeding method and rate; application rates of farmyard manure; use and rates of mineral N, P, and K fertilizers; application of micronutrient fertilizers; and irrigation method (gravity vs. sprinkler) and frequency.

We excluded the parameter "location" for the site at El Nubariyah in the "new land" due to the limited sample size of only 9 respondents. The location variable was also excluded from the general analysis to avoid results being influenced by random errors in the data [16] but also due to the absence of significant effects on wheat yields across the four study areas (Figure 2). Finally, predictor variables with values of "0" (no variability in the data set) were not considered. These concerned the seeding method (all manual broadcast), the tillage depth, the use of K fertilizer, and the application of micronutrients.

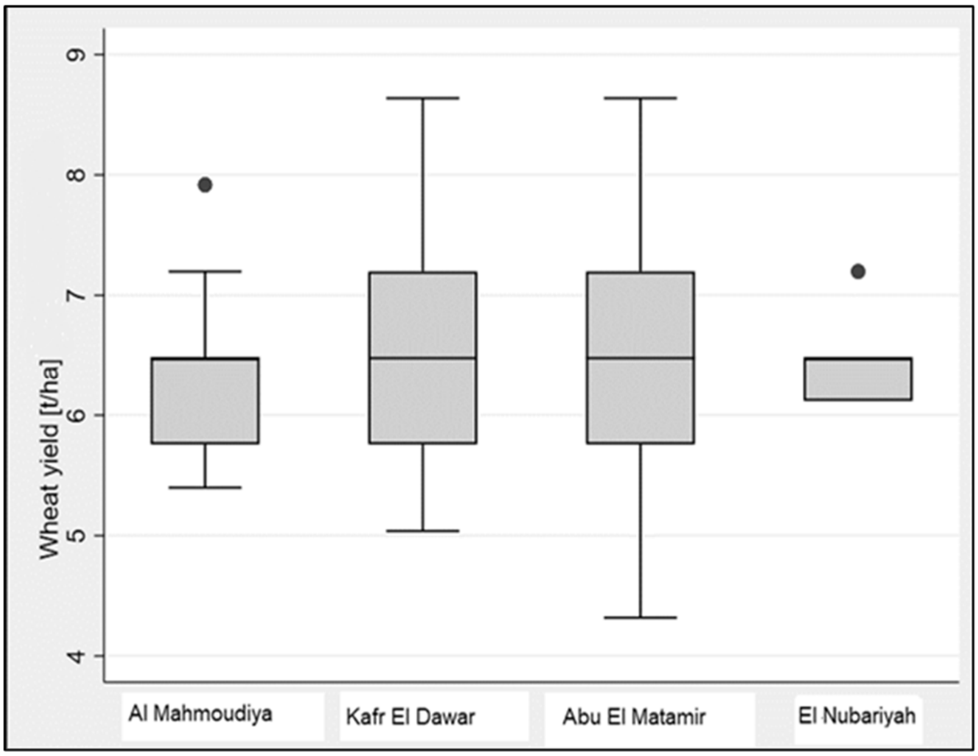

Figure 2. Wheat yield and yield variability in the four study areas in Egypt (survey 2021/22).

The robust method identified outliers to minimize their effect on data estimates, variance, and errors across predictor variables [16]. To detect the multi-collinearity, we ensured that variance inflation factors (VIF) were <10 [15]. Cook's D method prevented "influential" value-distorting generalizations [17]. The normality of data distribution and the stability of regression coefficients were tested via bootstrap [18]. Finally, pairwise comparisons identified the effect of predictor variables on wheat yield [19,20].

3. Results

3.1. Farmer Attributes and Resource Endowment

Attributes of wheat-producing farmers and their endowment with production resources (land, labor, capital) strongly varied between farms. In our study, we employed proxy measures for actual capital investment such as the use of labor force, land size, and amount of fertilizer. Our findings revealed that land size had a significant and positive influence on wheat productivity, indicating that farmers with larger landholdings were able to produce greater amounts of wheat per hectare. Moreover, we found that the availability of labor had a positive impact on productivity, implying that farmers with greater access to labor were better able to manage their crops. Furthermore, the results demonstrate that farmers with greater financial resources were able to invest in inputs such as fertilizers, which resulted in higher yields. Conversely, our statistical analysis indicates that there were no significant differences across farmer age and years of experience, and the variations in wheat yield. Farmers were middle-aged, with a mean age of 56 years (variation of 32–79 years), and with a mean experience in wheat cultivation of about 30 years. Moreover, the mean landholding size of 2.5 feddan (1.05 ha) varied greatly from 0.2 to 2.3 ha. The share of the land area occupied by wheat was 0.5 feddan, corresponding to 20% of their total landholdings, the remaining area was occupied by other winter crops, mainly by clover and broad beans. Wheat farmers depend largely on labor provided by family members and neighbors for tillage and fieldwork during the growing seasons. Improved varieties of modern high-yield wheat are, in most cases, obtained from local units of the Ministry of Agriculture, and, in some cases, farmers use self-grown seeds from the previous harvest (Table 1).

Table 1. Key characteristics of wheat-growing smallholder farms (survey of 2020/21).

	Age of Farmer (Years)	Farming Experience (Years)	Farm Size (ha)	Wheat Yield (t/ha)
Mean	56	30	1.05	6.4
Range	47	40	2.1	4.2
Minimum	32	10	0.2	4.2
Maximum	79	50	2.3	8.5
Count (n)	246	246	246	246

Farmers receive mineral nitrogen fertilizers at subsidized prices from the local agricultural co-operatives, while other external inputs (e.g., agrochemicals) must be bought on private markets. Applied organic amendments concern mainly farmyard manure from farmers' own livestock. Most farmers have adequate access to machinery services for soil tillage and harvest. However, access to knowledge regarding modern production technologies and to agriculture extension services is very poor. Farmers use the largest share (65%) of their wheat production for home consumption (subsistence-orientation), while the wheat straw is fed to livestock. Only about one third (35%) of the whole grain production is commercialized and sold to intermediaries and wheat traders to be stored in government silos.

3.2. Wheat Yield and Agronomic Practices

The average yield of wheat in 2021 was 6.4 t/ha, with a minimum of 4.2 t/ha and a maximum of 8.5 t/ha and rather little variation between the study areas (Figure 2). Yields varied according to agronomic practices applied, with the largest variations, and, hence, the largest uncertainties in the outcome of investments, in the dry and strictly rural desert margin site at Abu El Matamir, and the least variation at sites with good access to irrigation water (Al Mahmoudiya in the "old land" and El Nubariyah in the "new land"). The rates of adoption of agronomic practices reflect farmers' adaptive capacity to changing conditions and for meeting their aspirations and expectations. They concern the type of crop rotation, seed sources, the mechanization of tillage and harvest operations, and the use of agro-chemicals.

Wheat grows during the winter season (November to April) and is usually cultivated in rotation with (irrigated) summer crops. These summer crops differ by soil types. Thus, farmers cultivate maize and rice during the hot summer season on heavy clay soils in the divisions of El Mahmoudiyah and Kafr El Dawar, while maize and sunflowers dominate the summer crops on loam soils in Abo El Matamir, and peanuts, potatoes, and sesame dominate on the sandy soil of Nubaria divisions. These crops also differ in their field occupancy times, and the late harvest of long-duration crops can delay a timely establishment of the wheat crop.

While the recommended time for wheat seeding in the study areas is mid-November, seeding times in the sample ranged from early November to late December. Delays in seeding are related to crop rotations (late harvest of the summer crop), the untimely availability of machinery services for soil tillage, low labor availability, and late provision of subsidized inputs (mainly mineral N) from agricultural co-operatives.

The application of organic amendments (mainly farmyard manure) and of mineral P fertilizers (where applicable) precedes soil tillage by tractors, while wheat is seeded by manual broadcasting. Mineral N fertilizers are usually split-applied, with a first dose received after seedling emergence and subsequent applications before irrigation events. None of the interviewed farmers applied potassium or micronutrient fertilizers. Water in the "old land" is applied via flood irrigation by using water pumps from canals, while overhead sprinkler irrigation dominates the water supply in the "new land". The number of irrigation events during the wheat-growing season differed by site and soil types, ranging from one to five applications on clay soils in the "old land" and five to nine applications on sandy soils in the "new land".

The results of the multiple regression model that was employed to determine the effects of agronomic practices on wheat productivity show the high and significant value of the coefficients of multiple determination (R^2) for the predictor variables "preceding summer crop", "wheat seeding rate", "manure amount", "irrigation frequency", "mineral N application rate", and "P fertilizer use" (Table 2). These variables explain 59% of the total observed variation in wheat yield in the model. The following paragraph dissects individual agronomic practices regarding their effectiveness in improving wheat yields.

Table 2. Multiple regression estimates of effects of agronomic practices on wheat yield in Egypt (survey of 2020/21).

Variable	Df	F Value	P > f
Preceding crop (category)	4	7.5	0.001
Seeding rate (kg/ha)	3	3.74	0.012
Manure amount (t/ha)	3	4.31	0.006
Irrigation frequency (#)	3	38.31	0.001
Mineral n rate (kg/ha)	4	2.68	0.033
Mineral *p* rate (kg/ha)	5	3.19	0.008
Denominator	212		

3.3. Individual Yield-Affecting Variables

3.3.1. Crop Rotation

The preceding crop variable refers to the crop rotation and to the summer crop that is cultivated before wheat. The crop cultivated in rotation with wheat significantly impacted wheat productivity at 5% probability, explaining >7% of the total variation in wheat yield (Table 3). The highest wheat yield of 6.7 t/ha (range: 6.1–7.3 t/ha) was observed when wheat was cultivated in rotation with potatoes. This was followed by maize, rice, sunflower, and sesame with mean productivities of 6.4, 6.2, 5.8, and 5.5 t/ha, respectively.

Table 3. Effect of different summer crops grown in rotation with wheat on grain yield response of wheat in Egypt (survey of 2020/21).

Preceding Summer Crop	Wheat Yield (t/ha)	Standard Error	T	P > t	[95% Conf. Interval]	
Rice	6.27 ^{b}	0.078	80.2	<0.001	6.11	6.42
Maize	6.44 ^{ab}	0.075	85.6	<0.001	6.30	6.59
Sesame	5.51 ^{c}	0.260	21.2	<0.001	5.00	6.03
Potatoes	6.73 ^{a}	0.301	22.3	<0.001	6.14	7.33
Sunflower	5.83 ^{bc}	0.184	31.6	<0.001	5.47	6.20

Different letters denote significant yield differences by Tukey Test (0.05).

3.3.2. Seeding Rate

The amount of wheat seeds that smallholder farmers broadcast in each season varied between 90 and 170 kg/ha. High seeding rates were not related to increased yields, and the variable "seeding rate" explains only <4% of the total variation in wheat yield (Table 4). Actually, smallholders obtained the highest wheat yields (6.6 t/ha) with the lowest seeding rates (95 kg/ha). However, most farmers (>52%) exceeded this amount, using on average 120 kg/ha.

Table 4. Effect of seeding rates on grain yield response of wheat in Egypt (survey 2020/21).

Seeding Rate (kg/ha)	Wheat Yield (t/ha)	Standard Error	T	P > t	[95% Conf. Int.]		Share (%)
>100	6.56 [a]	0.0780	83.25	<0.001	6.414	6.72	29.3
100–130	6.33 [ab]	0.0512	123.72	<0.001	6.23	6.44	52.0
130–150	6.43 [a]	0.0996	64.59	<0.001	6.23	6.63	17.9
<150	6.06 [b]	0.1421	42.65	<0.001	5.78	6.34	0.8

Different letters denote significant yield differences by Tukey Test (0.05).

3.3.3. Organic Amendments

Most smallholders apply farmyard manure as an organic fertilizer source. The amounts applied are positively and significantly related to "wheat productivity", explaining 4% of the total variation in wheat yield (Table 1). Increasing application rates of farmyard manure can enhance soil fertility and soil water-holding capacity and were shown to increase wheat yields up to 6.7 t/ha with 20 t/ha of manure. However, such large amounts were used by only <12% of the farmers in the sample (Table 5).

Table 5. Effect of farmyard manure on grain yield response of wheat in Egypt (survey 2020/21).

Manure Applied (m^3/ha)	Wheat Yield (t/ha)	Standard Error	T	P > t	[95% Conf. Interval]		Share (%)
NONE	6.25 [b]	0.121	52.6	<0.001	6.11	6.58	14.2
8	6.27 [b]	0.070	89.5	<0.001	6.13	6.40	36.6
16	6.51 [ab]	0.072	90.2	<0.001	6.37	6.65	35.4
20	6.79 [a]	0.101	66.1	<0.001	6.49	6.89	11.8

Different letters denote significant yield differences by Tukey Test (0.05).

3.3.4. Irrigation Frequency

Exact amounts of applied irrigation water could not be assessed through the survey, and thus, we used the frequency of applied irrigation events as a proxy for water availability and crop supply. The number of irrigation events within one wheat-growing season was significantly related to total factor productivity, explaining 38% of the total variation in wheat yield (Table 6). The results reveal that 5 irrigation events or more during the wheat-growing season provide an average yield of 7.8 t/ha (range: 7.4–8.1 t/ha). However, the majority of wheat farmers (>59%) irrigate only twice per season, and only 7% apply 5 or more irrigation events.

Table 6. Effect of the number of irrigation events per season on the grain yield response of wheat in Egypt (survey 2020/21).

Irrigation Events	Wheat Yield (t/ha)	Standard Error	T	P > t	[95% Conf. Interval]		Share (%)
Once	5.82 [c]	0.1049	55.5	<0.001	5.62	6.03	18.3
Twice	6.36 [b]	0.0473	134.5	<0.001	6.26	6.45	58.5
3–4 times	6.81 [b]	0.1462	46.7	<0.001	6.53	7.10	12.6
≥5 times	7.83 [a]	0.1762	44.4	<0.001	7.48	8.17	6.9

Different letters denote significant yield differences by Tukey Test (0.05).

3.3.5. Mineral N Fertilizer

The rates of mineral fertilizer nitrogen (primarily in the form of ammonium nitrate) applied to wheat were very high, ranging from 200 to >580 kg N/ha. This figure represents an excess of the rates of N removed at the current grain yield levels of about 6 t/ha, corresponding to about 120 kg N/ha absorbed by the wheat crop. Consequently, no significant yield response to applied N rates was observed (over-supply with subsidized N fertilizer), and about one third of all farmers (34%) applied amounts in excess of 350 kg/ha (Table 7).

Table 7. Effect of different rates of applied mineral nitrogen on grain yield response of wheat (survey 2020/21).

N Application Rate (kg/ha)	Wheat Yield (t/ha)	Standard Error	T	P > t	[95% Conf. Int.]		Share (%)
>250	6.24 [ab]	0.091	68.05	<0.001	6.06	6.42	29.7
250–400	6.27 [ab]	0.077	81.97	<0.001	6.12	6.42	33.7
400–550	6.38 [a]	0.083	76.75	<0.001	6.22	6.54	23.9
<550	6.12 [b]	0.095	64.42	<0.001	5.93	6.30	12.6

Different letters denote significant yield differences by Tukey Test (0.05).

3.3.6. Mineral P Fertilizer

Mineral P fertilizers were usually applied as (P_2O^5) single-super-phosphate at rates of 100–300 kg P/ha. Similar to the corresponding rates for mineral N, these rates are by far in excess of the P demand of wheat, which, at the current wheat yields, rarely exceeds 15 kg P/ha. Thus, no clear yield response with increasing P application rates is apparent. The use of P fertilizer explains <3% of the total variation in wheat yield (ns), and the highest yields were obtained with the lowest P application rates (Table 8).

Table 8. Effect of different rates of mineral phosphate application on wheat yield response in Egypt (survey 2020/21).

P Application (kg/ha)	Wheat Yield (t/ha)	Standard Error	t	P > t	[95% Conf. Interval]		Share (%)
>150	6.64 [a]	0.121	54.7	<0.001	6.40	6.88	26.0
150–210	6.26 [b]	0.152	41.1	<0.001	5.96	6.56	10.2
210–260	6.27 [b]	0.056	110.2	<0.001	6.06	6.28	42.7
260–300	6.30 [ab]	0.134	47.7	<0.001	6.13	6.66	11.8
<300	6.34 [ab]	0.100	63.0	<0.001	6.14	6.54	9.4

Different letters denote significant yield differences by Tukey Test (0.05).

We can summarize that Egyptian wheat farmers are rather elderly and land-strapped, with little access to knowledge about intensified production technologies. Consequently, some (subsidized) inputs such as N and P fertilizers and improved wheat seeds are applied in excessive and non-yield-effective amounts. The type of crop rotation, the amount of applied farmyard manure, and the number of irrigation events are the most yield-effective agronomic practices that warrant more future attention (Figure 3).

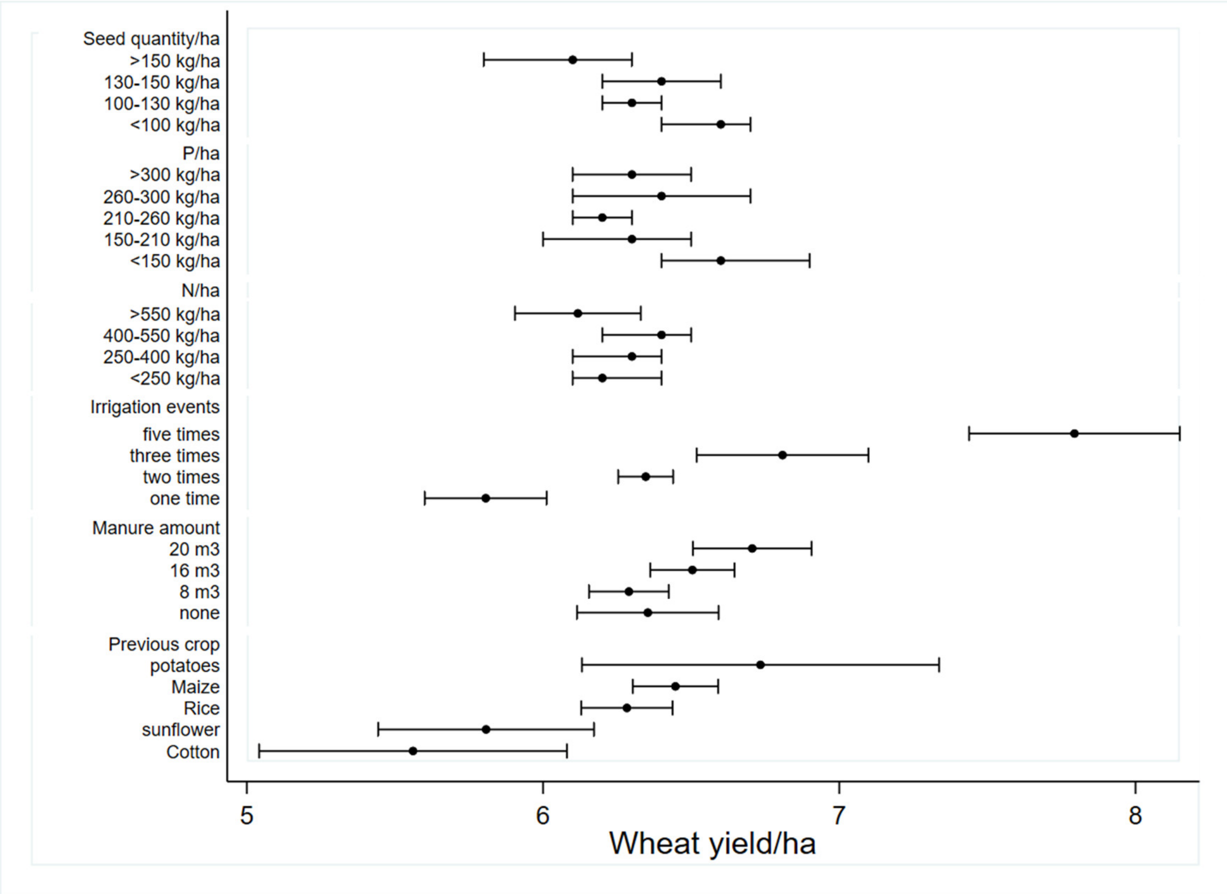

Figure 3. Wheat yield response to the individual agronomic variables in the four study areas in Egypt (survey 2021/22).

4. Discussion

Increasing the domestic wheat production is imperative for Egypt in view of disrupted wheat value chains and soaring wheat prices on international markets in relation to the Russia–Ukraine war. An expansion of the irrigated cropland area is limited by water availability. Two options for moving toward achieving national self-sufficiency in wheat concern (1) increasing the area share under wheat cultivation, mainly by replacing winter clover and by wheat, and (2) increasing wheat yields on existing irrigated cropland.

4.1. Increasing Wheat Production

Only <20% of the irrigated winter cropland area in the study area is currently cultivated with wheat, compared to nearly 30% in China [21], 42% in Europe [22], and up to 60% in South Asia [23]. Replacing Alexandrian clover (berseem) with wheat as the dominant winter crop could potentially increase the cultivated wheat area by up to 0.6 million ha in the Nile Delta [24], thus effectively counteracting current shortfalls in wheat imports. This is, however, no stand-alone strategy, as it would strongly affect feed production and, thus, jeopardize the supply with meat and milk, shifting the bread shortage to a protein shortage problem. In addition, strong fiscal incentives would be needed to substantially increase the economic attractiveness of wheat cultivation. For instance, the net income of cultivating one feddan (0.4 ha) of wheat was estimated at EGP 2991 (equivalent to USD 178) in 2019 [25]. This means that smallholders receive a monthly net income of only USD 29 from cultivating one feddan of wheat. Such low economic attractiveness of wheat production has been highlighted by local purchasing prices being strongly correlated with the cultivated area of wheat in Egypt [6].

Consequently, the wheat area is expected to expand with increasing farm gate prices for wheat. Policies increasing the economic attractiveness of producing wheat are urgently required. Beyond such economic incentives, it appears paramount to also increase the social acceptance and recognition of farming for the younger generation [26]. A mean age of wheat farmers of 56 years, compared to the mean age of 26 years of the whole population in Egypt [27], highlights the lack of interest in farming among the younger generation [28]. This trend, if not reversed, may jeopardize the future of agriculture and food production in Egypt and possibly beyond [29].

On the other hand, with an average yield of about 6 t/ha, wheat farmers in the Nile Delta of Egypt produce far below the yield potential and below the yield level achievable on a research station or by a small number of progressive farmers [30]. We hypothesized that poor land, water, and crop management practices are responsible for the currently large yield gaps [31], and we investigated possible reasons and ways forward toward achieving wheat self-sufficiency.

4.2. Unbalanced Nutrient Supply

Nitrogen and P fertilizers are applied far in excess of the nutrient uptake or crop demand [32] of about 23 kg N and 2.2 kg P per ton of wheat grain [33]. With an aver-age of 6.5 t/ha in El Beheira Governorate, this figure implies that 140 kg N and 16 kg P/ha are needed to compensate for current rates of nutrient removal. At mean rates of 300 kg N and 95 kg P/ha, the current application exceeds crop demands by factors of 2.5 (nitrogen) and 6 (phosphorus). Excessive application rates of mineral N and P ferti-lizers appear to induce an imbalance in the provision of other plant nutrients. Thus, micronutrients are widely deficient in soils of the "old land" (mainly Zn) [34], and in the "new land" (mainly Mn, Fe, B, and Zn) [35]. Such micronutrient deficiencies are reportedly affecting yields of wheat [36] and other crops [37]. The current subsidy pol-icies favor unbalanced wheat nutrition and need to be amended by supporting farmers with K fertilizers while encouraging the development of new and balanced micronu-trient fertilizer formulations.

In addition, excessive and wasteful nutrient applications entail widespread N- and P-related environmental problems [38] and water pollution in Egypt [39]. According to El Kader [40], the use of excessive amounts of N and P fertilizers has en-tailed serious recent environmental consequences. The associated eutrophication of surface water bodies has resulted in the growth of harmful algae, the depletion of oxy-gen, and the death of fish and other aquatic organisms. In addition, eutrophication affects the quality of drinking water and entails a further exceeding of the planetary boundaries [41].

4.3. Water Deficit

Irrigation water is key to high and stable wheat yields. Our data showed that different irrigation strategies and frequencies are by far the most yield-effective production factor, explaining nearly 40% of the observed yield variability. This is particularly relevant in water-strapped environments in the desert margin (i.e., Abu El Matamir Division) and in soils with low water-holding capacities (i.e., Kafr El Dawar Division). In those areas, large observed yield variabilities are related to poor or unreliable water supply and increase the riskiness of production or the uncertainty in the outcome of investments in agricultural production. Given prevailing water limitations and growing competition for water resources from industry and urban development, water for agriculture in general and for wheat production specifically must be used more efficiently. This may be achieved by restricting wasteful overhead sprinkler applications (i.e., use of drip irrigation) [42], by encouraging the use of effective agronomic production methods (i.e., mulch culture) [43], and by using water-efficient wheat genotypes [44]. Yet another strategy concerns retaining water in the soil matrix by increasing organic matter contents. Current application rates of organic amendments (i.e., farmyard manure) are rather low but are required for improving soil water-holding capacities [45], particularly on the sandy soils in the "new land" [46]. Finally, applying raised-bed technologies can have a significant impact on wheat production under conditions of water shortages by reducing crop water use by up to 25% while increasing wheat grain yields [47]. Most of these strategies are knowledge-intensive, requiring training of farmers, strengthening extension, and generally improving farmers' access to modern production technologies.

4.4. Future Needs

Expanding the area cultivated with wheat and increasing grain yields per unit area require effective policy interventions, ensuring incentivizing wheat prices (similar or above the price of imported wheat, which is often of lesser quality). Farmers may be encouraged to cultivate larger shares of their holdings with wheat when fixed price ceilings are declared before the beginning of the cultivation season. Yields can increase and yield variability, and hence, uncertainties may be reduced by new micronutrient-containing fertilizer formulations. The use of such fertilizers may be stimulated by providing them at subsidized prices.. Additionally, the development and extension of wheat genotypes with higher drought tolerance or better water use efficiency should be a high priority for the Ministry of Agriculture and Land Reclamation and relevant research institutions in Egypt.

The highly varied application rates of amendments and farm inputs and the overuse of some mineral fertilizers (in this case, mainly mineral N and P) also reflect a lack of knowledge at the farmer's level. There is an urgent need to improve agricultural extension services to provide relevant information, training, and technology recommendations to wheat-producing farmers. This also entails improved and location-specific recommendations of fertilizer types and rates; of irrigation frequencies; and of the preparation, storage, and application of organic amendments.

The implementation of policies that provide incentives to farmers to expand their wheat-growing area and adopt sustainable agricultural technologies has the potential to significantly increase domestic wheat production and reduce dependence on costly and inconsistent wheat imports. These policies may include measures such as subsidies or tax breaks for investments in agricultural technology and equipment, support for the research and development of new and improved wheat varieties, and funding for extension services to provide farmers with the necessary information and resources to optimize their agricultural practices. Moreover, strengthening agriculture extension services is a critical component of any policy designed to increase wheat productivity. Extension services provide farmers with access to knowledge and training on the best practices for crop management, pest control, and soil fertility management. By adopting more advanced technologies and practices, farmers can improve their yields and produce higher-quality crops.

While a substantial amount of research has been conducted on wheat production in Egypt, there are several areas requiring further study to improve wheat productivity and ensure food security:

(1) Climate Change: Climate change is expected to affect wheat production in Egypt, particularly in terms of water availability and quality. Future studies should focus on identifying effective adaptation strategies for wheat production in a changing climate, including the development of drought-tolerant wheat varieties and improving water management practices.
(2) Soil Health: Soil health is critical for sustainable agriculture and wheat productivity. Future studies should investigate the impact of practices such as cover cropping, crop rotation, mulch culture, and reduced tillage to foster soil health, nutrient cycling, and the water-holding capacity of wheat soils.
(3) Market Access: Improving market access and facilitating trade is critical for ensuring that wheat farmers receive fair prices for their crops. Future studies should examine factors influencing market access and trade, including policy and infrastructure barriers.
(4) Technology Adoption: Technology adoption is critical for improving wheat productivity in Egypt. Future studies should investigate factors influencing farmers' adaptive capacity to adopting site-specifically adapted new technologies.

5. Conclusions

In conclusion, the present study identified inappropriate agricultural practices that are related primarily to irrigation and fertilization scheduling and intake as key factors contributing to the low yields that result from a lack of knowledge and extension services. However, through the implementation of sustainable irrigation and fertilization practices, there is a high potential for a substantial increase in yields and, consequently, the total domestic wheat production in Egypt. Increasing domestic wheat production in Egypt is imperative to reduce the increasing economic burden of wheat imports, to support farmers' livelihoods, and to render the country more resilient to disruptions in the international wheat supply chains. Two promising strategies concern (1) an increase in the area share cultivated to wheat via partial substitution of berseem clover with wheat as the dominant winter crop and (2) implementing effective and sustainable agronomic practices to reduce the yield gap while increasing farmers' income.

Although improving wheat productivity among smallholder farmers in Egypt is critical to achieving food security and reducing poverty in the country, smallholder farmers face numerous challenges, including limited access to knowledge, technology, markets, and credit facilities, which limit their productivity. To address these challenges, it is essential to implement comprehensive approaches that include providing extension services, increasing access to credit, improving access to markets, and promoting the use of appropriate technologies. In addition, efforts should be directed toward developing appropriate policies and strategies that support smallholder farmers, such as pricing policies that provide them with fair returns and infrastructure development that supports agricultural productivity. These interventions need to be accompanied by targeted capacity-building programs that equip farmers with the necessary knowledge and skills to adopt new technologies and practices that enhance productivity. Moreover, given the importance of wheat in the Egyptian diet, there is a need to invest in research and development to develop new wheat varieties that are more resilient to changing climatic conditions, water scarcity, and pests.

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Institutional Review Board Statement: This study was approved by the Institutional Review Board at the Research Ethics Committee, Center for Development Research (ZEF), the University of Bonn, (protocol code: Ethical Clearance Form for BIGS-DR doctoral program—Guidance Note. on 15th September 2020. All participants provided informed consent prior to participating in the study. The study protocol was designed for studies involving humans to minimize any potential risks to participants, and their confidentiality was protected throughout the research process.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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