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Correlation, direct and indirect effects on grain yield of wheat genotypes under drought stress and normal irrigation conditions

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ABSTRACT

The study assessed three Egyptian wheat genotypes under varying irrigation levels, including full irrigation (I100%) and drought conditions (I80% and I60% of crop evapotranspiration, ETC). Field experiments were carried out at the experimental farm of the Faculty of Agriculture, Fayoum University, Egypt, throughout the 2020–2021 and 2021–2022 growing seasons. Positive correlations with grain yield were observed under optimal irrigation, emphasizing the importance of traits such as plant height, spike length, and grain weight per spike. Mild stress conditions (I80%) revealed significant associations with tiller-related traits, spike characteristics, and yield components, while severe stress conditions (I60%) demonstrated robust positive correlations with all traits except total tiller number (NTT). Specific traits, including NTT and NSM2, exhibited positive direct effects on grain yield, while others, such as plant height (PH), had unfavorable direct effects. Positive indirect impacts on grain yield were identified through various pathways. Harvest Index (HI %) and biological yield per feddan (BYF) were pivotal under water stress (I80%), with positive indirect effects observed. Severe water stress (I60%) highlighted the substantial impact of HI% and positive indirect effects for other traits. The study recommends focusing on these key traits for genetic enhancements to enhance grain yield in bread wheat varieties under stress environmental conditions.

1. Introduction

Wheat (*Triticum aestivum* L.) stands as the paramount grain crop on a global scale, playing a pivotal role as a fundamental food source for approximately 40% of the world's population [1]. It currently holds the distinction of being the most widely cultivated crop, spanning more than 216 million hectares and yielding an annual production of 766 million tons [2]. In Egypt, the cultivation of wheat spans 1.4 million hectares, yielding a robust production of 9 million tons [2]. Notably, Egypt holds the distinction of being the world's largest importer of wheat, a demand fueled by its significant consumption of bread. Bridging the substantial gap between wheat production and consumption is imperative for wheat scientists, as they strive to align cultivation with the nation's burgeoning needs.

The measurement of the relationship between traits can be done using phenotypic correlation coefficients. However, correlation coefficient analysis might not accurately determine the precise significance of the direct and indirect influences of each yield component on grain yield. On the other hand, path coefficient analysis assesses the direct and indirect impacts of independent variables on dependent variables. This analysis assists breeders in understanding the underlying causes of associations between two variables [3]. Positive and significant correlations between specific traits and grain yield at a phenotypic level. Notably, harvest index, fertile tiller per plant, spike length, and the number of spikelets per spike displayed a strong positive correlation with grain yield, indicating a shared genetic influence on these traits and their contribution to increased grain yield. Under optimal conditions, the harvest index demonstrated a robust positive direct effect (0.626) on grain yield, emphasizing its crucial role in influencing productivity. Remarkably, even under stressful conditions, the harvest index maintained a moderately positive direct effect (0.214) on grain yield. These findings imply that genetic improvements targeting harvest index, fertile tiller per plant, spike length, and spikelet number could be pivotal for enhancing grain yield in bread wheat genotypes, providing valuable insights for future breeding strategies [4].

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Recurrent drought is the primary abiotic stress factor that significantly reduces wheat production and productivity [1]. This stress can cause yield losses ranging from 17 to 70% in wheat [5]. As a result, the farming community suffers substantial economic losses [6]. To improve a specific trait, it is not sufficient to directly select for that trait alone. Indirect selection through other more heritable and easily measurable traits is also necessary. This selection strategy requires a comprehensive understanding of the correlations among different characters and how they relate to other traits.

The present study aimed to evaluate the relationship between agronomic traits and their direct and indirect impact on grain yield of bread wheat under normal and stress conditions.

2. Materials and Methods

2.1. Location

Two experiments were conducted at the experimental farm of the Faculty of Agriculture, Fayoum University (29°17’38" N, 30°54’55" E) during the 2020/2021 and 2021/2022 seasons. The soil texture analysis was 76.50% sand, 13.39 silt, 10.11% clay, and it is considered as sandy loam soil. The soil ECe (electrical conductivity) was 3.42 dS m-1. The soil is slightly alkaline in pH (7.80), 0.98% for organic matter content, 8.26% for CaCO3%, 0.04% for N, available K and P was 45.4, and 4.42 meq 100–1 g soil, respectively

2.2 Experimental design and treatments

The experiment conducted was a split-split plot design within a randomized complete block design with three replications. The main plots consisted of three irrigation treatments, namely normal irrigation, 100% (I100%), mild stress condition, 80% (I80%), and severe stress, 60% (I60%). The sub-plots involved different farming systems, specifically raised beds of 100 cm, raised beds of 60 cm, and cultivation on a flat. Additionally, the sub-sub plots were assigned to different wheat genotypes i.e. Giza-171, Sids-12, and Lin-3, which served as the most crucial factor at this level of the experimental design. The study employed wheat varieties, Giza-171 and Sids-12, sourced from the Wheat Department at the Agricultural Research Center in Giza, Egypt, along with Line-3, a previously developed line by Ghallab [7]. The experimental plot was 3 meters long × a row width of 3.5 meters (10.5 m2), and the distance between plants within rows was 15 centimeters.

2.3. Agronomic traits

At the harvest stage, ten representative plants were randomly selected from each plot, and the following traits were measured: plant height (PH) in centimeters, total tiller number (NTT), fertile tiller number (NFT), spike length (SL) in centimeters, number of spikelets for the main stem spike (SS), number of grains for the main stem spike (GS), grain weight per spike (GWS) in grams, 1000-grain weight (SGW) in grams, and grain yield per plant (GYP) in grams. Additionally, on a plot basis, the recorded traits included the number of spikes /m2 (NSM2), biological yield per feddan (BYF) in tons, grain yield per feddan (GYF) in tons, and harvest index (HI %).

2.4. Data Analysis

2.4.1. Correlation and Path coefficient analysis

Phenotypic correlation analysis was conducted following Pearson's correlation coefficient between all possible pairs of quantitative traits and their direct and indirect effect of the independent variables on grain yield at the phenotypic level were analyzed using IMB SPSS version 21 [8].

$$rp = \frac{\text{p cov xy}}{\sqrt{\sigma^2 \text{px} * \sigma^2 \text{py}}}$$

Where *rp* is phenotypic correlation coefficients, *p cov x.y* is phenotypic covariance between variables *x* and *y*, σ2 *px* is the phenotypic variance for variable *x* and σ2*py* is the phenotypic variance for variable *y*.

2.4.2. Path coefficient Analysis

Path coefficient analysis was computed for each parameter separately to partition the correlation coefficient to direct and indirect effects of the components on bread wheat yield as illustrated by Dewey and Lu [9].

$$rij=pij+\sum rikpkj$$

where, rij=correlation between the independent character (i) and dependent character(j) as measured by the correlation coefficient. pij=Components of direct effects of the independent character (i) on the dependent character (j) as measured by the path coefficient. ∑rikpkj=summation of components of an indirect effect of a given independent character (i) on the given independent character (j) via all other independent characters (k).

The residual effect, which determines how best the causal factors account for the Variability of the dependent factor, was calculated using the following formula:

$$1=p2r+\sum piy.riy$$

Where: p2r=is the residual factor, piy is the direct effect of yield with ith trait. riy is the correlation of yield with the ith trait.

Path coefficient analysis was used to determine the scales for path coefficients. In the context of rice, path coefficient values ranging from 0.00 to 0.09 were deemed negligible, 0.10 to 0.19 were considered low, 0.20 to 0.29 were classified as moderate, and 0.30 to 0.99 were regarded as high path coefficients.

3. Results

3.1 Correlation Coefficient Estimates

Table 1 showed the magnitude of the relationship among the quantitative traits. The results indicate a highly significant association among all the traits, except for the correlation between SS with GWS and SGW, which was found to be significant. This association is observed under both stress and non-stress conditions. Additionally, grain yield exhibits a highly significant positive correlation with all the examined traits, irrespective of stress conditions (above the diagonal in Table 1).

Under optimum irrigation (I100%), grain yield showed significant positive correlations with plant height (PH) (r=0.331*), spike length (SL) (r= 0.272*), and grain weight per spike (GWS) (r=0.309*). However, it exhibited highly significant correlations with tiller number (NTT) (r=0.734**), fertile tiller number (NFT) (r=0.734**), spikelets per spike (SS) (r=0.797**), grain yield per plant (GYP) (r=0.399**), grains per spike (GS) (r=0.465**), spikes per square meter (NSM2) (r=0.710**), biological yield per feddan (BYF) (r= 0.453**), and harvest index (HI %) (r=0.366**) as indicated in the low diagonal values of Table 1.

Under mild stress conditions (I80%), the correlation analysis revealed highly significant and positive associations between grain yield and several traits such as NTT (r=0.565**), NFT (r=0.565**), SS (r=0.481**), NSM2 (r=0.712**), BYF (r=0.678**), and HI % (r= 0.748**). Moreover, there were significant and positive correlations with PH (r=0.298*). In contrast, non-significant and negative correlations were observed with GWS (r= -0.023) and SGW (r= -0.041). Additionally, non-significant positive correlations were found with SL (r= 0.212) and GYP (r= 0.195) as presented above the diagonal of Table (2).

Table 1: Estimates of phenotypic correlation coefficients under stress and non-stress (above diagonal) and optimum condition, I100% (below diagonal), for bread wheat genotypes

Traits	PH	NTT	NFT	SL	SS	GYP	GS	GWS	SGW	NSM2	BYF	HI %	GYF
PH	1	.630**	.630**	.646**	.127	.752**	.378**	.530**	.279**	.588**	.592**	.738**	.685**
NTT	.331*	1	1.000**	.724**	.354**	.727**	.756**	.776**	.445**	.904**	.737**	.479**	.788**
NFT	.329*	1.000**	1	.724**	.354**	.727**	.756**	.776**	.445**	.904**	.737**	.479**	.788**
SL	.142	.135	.135	1	.172*	.620**	.677**	.727**	.274**	.681**	.676**	.441**	.708**
SS	.686**	.744**	.744**	.097	1	.147	.296**	.191*	.172*	.319**	.235**	.207**	.333**
GYP	-.475**	.398**	.398**	-.021	.479**	1	.615**	.710**	.562**	.780**	.750**	.611**	.818**
GS	-.207	.393**	.393**	.001	.609**	-.047	1	.888**	.513**	.797**	.702**	.176*	.705**
GWS	-.235	.305*	.305*	-.044	.439**	.193	.707**	1	.447**	.778**	.708**	.326**	.722**
SGW	.128	.150	.150	-.547**	.332*	.212	.200	.155	1	.649**	.488**	.202**	.523**
NSM2	.266	.758**	.758**	-.116	.844**	.446**	.436**	.379**	.502**	1	.779**	.464**	.842**
BYF	.774**	.375**	.375**	.305*	.328*	.276*	.144	.147	-.081	.313*	1	.509**	.845**
HI %	.236	.461**	.461**	.246	.181	.411**	-.399**	-.261	-.151	.234	.280*	1	.749**
GYF	.331*	.734**	.734**	.272*	.797**	.399**	.465**	.309*	.216	.710**	.453**	.366**	1

*&** Correlation is significant at the 0.05 and 0.01levels

Table 2: Estimates of phenotypic correlation coefficients under moderate stress, I80% (above diagonal), and severe stress, I60% (below diagonal) for bread wheat genotypes

Traits	PH	NTT	NFT	SL	SS	GYP	GS	GWS	SGW	NSM2	BYF	HI %	GYF
PH	1	.278*	.278*	.397**	-.033	.616**	-.300*	.106	-.043	.209	.129	.666**	.298*
NTT	.438**	1	1.000**	.490**	.592**	.410**	.282*	.502**	-.280*	.792**	.501**	.320*	.565**
NFT	.438**	1.000**	1	.490**	.592**	.410**	.282*	.502**	-.280*	.792**	.501**	.320*	.565**
SL	.398**	.645**	.645**	1	.054	.193	.095	.379**	-.412**	.303*	.121	.341*	.212
SS	.379**	.256	.256	.528**	1	.330*	.216	.086	.155	.634**	.397**	.075	.481**
GYP	.436**	.057	.057	-.005	.014	1	-.091	.229	.189	.428**	.143	.337*	.195
GS	.110	.298*	.298*	.460**	.689**	-.318*	1	.784**	-.507**	-.039	-.007	-.549**	-.256
GWS	.396**	.595**	.595**	.563**	.413**	.105	.605**	1	-.623**	.194	.097	-.124	-.023
SGW	-.149	-.403**	-.403**	-.114	.141	-.014	.166	.087	1	.037	-.068	-.046	-.041
NSM2	.444**	.783**	.783**	.695**	.533**	-.004	.357**	.498**	-.336*	1	.536**	.442**	.712**
BYF	.309*	.087	.087	.230	.440**	.406**	.279*	.336*	.137	.136	1	.346*	.678**
HI %	.758**	.247	.247	.240	.368**	.778**	-.092	.267	-.043	.320*	.429**	1	.748**
GYF	.689**	.286*	.286*	.374**	.566**	.690**	.141	.354**	-.049	.390**	.644**	.914**	1

*&** Correlation is significant at the 0.05 and 0.01levels

Under severe stress conditions (I60%), the correlation analysis, as presented in the lower diagonal of the Table (2), reveals robust and highly significant positive associations between grain yield and all studied traits, except for NTT, which showed a positive and significant correlation (r=0.286*). However, a non-significant negative correlation was observed with SGW (r= -0.049)

3.2 Phenotypic direct and indirect effects of traits on grain yield

Path analysis in wheat cultivars is a statistical method used to explore the direct and indirect relationships between various variables that might affect the performance of wheat varieties. Path analysis helps in understanding the complex interplay between different factors and how they contribute to the overall performance of wheat cultivars. The direct and indirect effects of different traits on grain yield are presented in (Fig. 1).

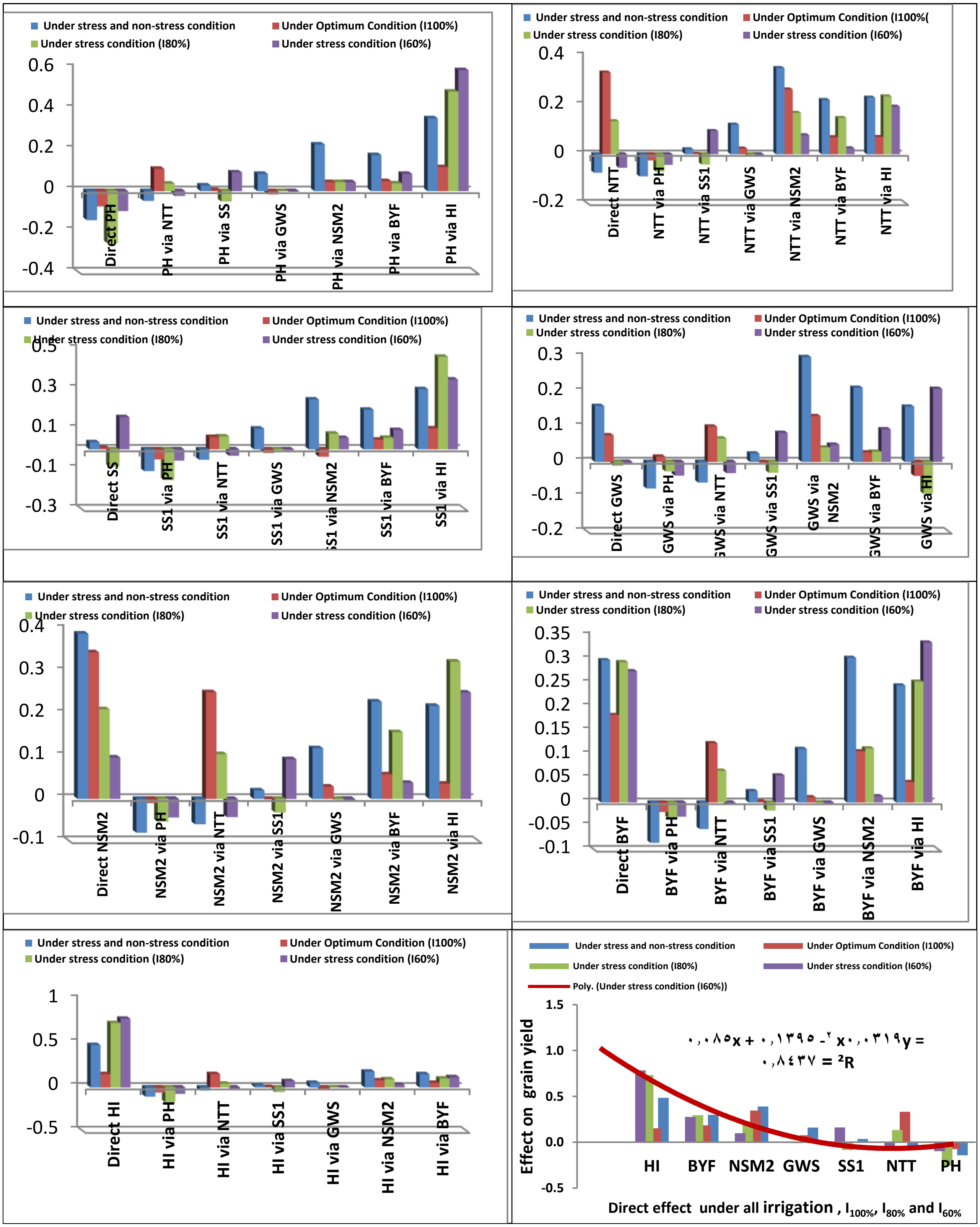

Fig 1. Estimates of direct and indirect effects under stress and non-stress irrigation of different traits on grain yield at phenotypic level in bread wheat genotype

3.2.1 Under stress and non-stress condition

Under all irrigation levels, the direct effects on grain yield were notable for certain traits. HI % (0.484) and NSM2 (0.390) showed the most positive direct effects, followed by BYF (0.299) and GS (0.160). On the other hand, NTT (−0.075) and PH (-0.143) had negative direct effects on grain yield. Interestingly, there were substantial positive indirect effects observed, such as the positive indirect effect of PH through HI% (0.357), NTT through BYF (0.350), BYF through NSM2 (0.304), and the joint positive effects of GWS through NSM2 and SS through HI % (0.300) on grain yield. These findings suggest a complex interplay of both direct and indirect effects of various traits on grain yield under different irrigation conditions (Fig. 1).

3.2.2 Under Optimum Condition (I_{100} %)

Regardless of the full irrigation level (I100%), certain traits exhibited notable positive direct effects on grain yield, ranked in the following order: NTT (0.332) and NSM2 (0.346), followed by BYF (0.184) and HI % (0.152). Conversely, traits like PH (-0.0075), had negative direct effects on grain yield. Interestingly, there were positive indirect effects on grain yield from NTT through NSM2 (0.263), GW through NSM2 (0.131), and NSM2 through NTT (0.253) as presented in (Fig. 1).

3.2.3 Under stress conditions (I80%)

Under water stress conditions (I80% irrigation), specific traits demonstrated direct positive impacts on grain yield, with HI % (0.733), BYF (0.295), and NSM2 (0.212) ranking as the most influential. Intriguingly, positive indirect effects on grain yield were observed through various pathways, including PH via HI % (0.488), SS through HI % (0.461), NSM2 through HI% (0.324), BYF through HI % (0.254), and NTT through HI % (0.235) traits (Fig. 1).

3.2.4 Under stress conditions (I_{60}%)

According to the coefficients, specific traits exhibited positive direct effects on grain yield under water stress (I60%). Harvest index (HI%) had the most substantial impact, with a coefficient of 0.783, followed by biological yield per Feddan [BYF] at 0.276 and spikes/m2 (SS) at 0.161. Additionally, there were notable positive indirect effects through various pathways, including plant height (PH) through HI%, SS through HI%, Number of Spikes /m2 (NSM2) through HI %, and BYF through HI%, with coefficients of 0.593, 0.348, 0.251, and 0.336, respectively (Fig. 1).

4. Discussion

In the current study, the findings reveal a highly significant association among all the traits, except for the correlation between SS with GWS and SGW, which was found to be significant. This association is observed under both stress and non-stress conditions. Additionally, grain yield demonstrates a highly significant positive correlation with all the examined traits, irrespective of stress conditions. This suggests a robust interdependence among the traits and underscores their collective impact on grain yield, reinforcing their importance across different environmental conditions [10-13].

The significant positive correlations observed between grain yield and various traits under optimum irrigation conditions (I100%) highlight the interconnected nature of these factors in influencing wheat productivity. The strong positive correlations with tiller-related traits (NTT and NFT) emphasize the importance of effective tillering in maximizing grain yield. Similarly, the positive associations with spike-related traits (SS, GS, and NSM2) indicate the role of spike characteristics in determining overall yield. The correlations with biological yield per feddan (BYF) and harvest index (HI%) further underscore the significance of these traits in influencing grain yield [12, 13-17]. Under mild stress conditions, positive correlations were observed between grain yield, with traits like NTT, NFT, SS, NSM2, BYF, HI%, and PH showing significant associations [18]. These findings are essential for understanding the plant's response to moderate water stress and identifying traits that play a significant role in maintaining productivity [13, 18, 19].

The strong positive correlations between grain yield and various traits under severe stress conditions (I60%) suggest the resilience and adaptability of the studied wheat genotypes to challenging environments. The positive and significant correlation of NTT highlights the importance of effective tillering even under stressful conditions. The non-significant negative correlation with SGW indicates a potential trade-off between certain traits and grain yield under severe stress [20 - 22]. In our study, we investigated the effects of different irrigation levels on grain yield. We found that under all irrigation conditions, certain traits had direct effects on grain yield, while others had indirect effects through another trait. The observed direct and indirect effects of various traits on grain yield under different irrigation levels present a complex and interconnected scenario. Harvest Index (HI%) and NSM2 emerge as influential factors with the most positive direct effects on grain yield under all irrigation conditions. This implies that a higher harvest index and a greater number of spikes /m2 contribute significantly to enhanced grain yield [23-26].

Conversely, traits like NTT and PH exhibit negative direct effects on grain yield. This suggests that an increase in tiller number and plant height may have adverse effects on grain yield, emphasizing the importance of optimising these traits for better productivity [17]. The positive indirect effects further highlight the interdependence of traits. For instance, the positive indirect effect of PH through HI% and NTT through BYF suggests that these traits indirectly contribute to grain yield through their impact on other influential factors. The joint positive effects of GWS through NSM2 and SS through HI% indicate a combined influence on grain yield, demonstrating the intricate relationships between different traits. Similarly, positive direct and indirect effects [8, 22]. The findings under water stress conditions (I80% irrigation) highlight specific traits that directly contribute positively to grain yield, with HI%, BYF, and NSM2 being the most influential. These traits play a crucial role in maintaining or enhancing wheat productivity, even under stress. The observed positive indirect effects through pathways such as PH via HI%, SS through HI%, NSM2 through HI%, BYF through HI%, and NTT through HI% suggest intricate relationships and interdependencies among these traits. This emphasizes the importance of considering multiple factors simultaneously when evaluating the impact of individual traits on grain yield under water stress conditions [16, 27-29]. In summary, these results provide insights into the specific traits that could be targeted for improving wheat yield resilience in the face of water stress.

The coefficients presented in the statement indicate the effects of specific traits on grain yield under water stress conditions (I60%). Positive coefficients indicate a positive direct effect, meaning that an increase in the trait leads to an increase in grain yield. The traits considered in this analysis are harvest index (HI %), biological yield per feddan (BYF), spikelets per spike (SS), plant height (PH), and number of spikes/m2 (NSM2). Additionally, there were indirect effects through various pathways. Plant height (PH) had an indirect effect on grain yield through the harvest index. This indicates that an increase in PH promotes a higher harvest index, which subsequently enhances grain yield [6, 17, 30].

5. Conclusion

The study revealed a robust interdependence among various traits and their collective impact on grain yield, regardless of stressful conditions. Positive correlations were observed under both optimum and stress conditions, emphasizing the importance of these traits in influencing wheat productivity. The investigation into different irrigation levels further highlighted the complex interactions, with certain traits demonstrating direct and indirect effects on grain yield. Harvest Index (HI%) and the number of spikes/m2 (NSM2) emerged as influential factors, contributing positively to grain yield across different irrigation conditions. The findings under water stress conditions pinpointed specific traits, such as HI %, biological yield per feddan (BYF), and NSM2, as crucial for maintaining or enhancing wheat productivity even under stress. The study contributes valuable insights for targeted trait improvement strategies, providing a foundation for enhancing wheat yield resilience in diverse environmental conditions.

Author Contributions

Conceptualization, K. H. Ghallab and M. A. Abd ELRady; Methodology, K. H. Ghallab , M. A. Abd ELRady and T. A. Abdel Mageed; Validation, K. H. Ghallab; Formal analysis, K. H. Ghallab; Investigation, M. A. ElSayed, M. A. Abd ELRady and T. A. Abdel Mageed; Data curation, K. H. Ghallab , M. A. ElSayed and T. A. Abdel Mageed; Writing—original draft preparation, K. H. Ghallab and T. A. Abdel Mageed; Writing—review and editing, K. H. Ghallab and T. A. Abdel Mageed; Visualization, K. H. Ghallab; Supervision, K. H. Ghallab , M. A. Abd ELRady and T. A. Abdel Mageed; Project administration K. H. Ghallab , M. A. Abd ELRady and T. A. Abdel Mageed; Funding acquisition, K. H. Ghallab and M. A. ElSayed. All authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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