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Impact of mycorrhizal and compost tea on wheat under water stress

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تأثير الفطريات الجذرية وشاي الكمبوست على القمح تحت الإجهاد المائي

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Abstract

In the winter of 2024–2025, this experiment was carried out on the farm owned by researcher Musa Muhammad Ibrahim in the Awlad Ali neighborhood of Tarhuna, Libya. The current study investigated the effects of three different mycorrhizal plus compost tea (CT) inoculation rates (15, 30, and 45%) and irrigation levels (100, 75, and 50%) on the wheat cultivar "Sakha 93." The treatments in the experiment were set up in a spilt-spilt plot design, with irrigation levels as the main plot and mycorrhizal + compost tea as the submain plot. There were three duplicates of each therapy. In comparison to the control treatment, which recorded the lowest values of these traits, the results demonstrated that 100% irrigation produced higher values of vegetative growth (plant height, dry weight/plant, leaf area index, and total chlorophyll), yield and yield components (spike length, number of spikes/m2, number of grains/spike, 100-grain weight, grain yield, biological yield and harvest index), and chemical composition (nitrogen, phosphorus, potassium, and protein percentages). High concentration of mycorrhizae (AMF) with compost tea (45 ml/l) In comparison to the control treatment, which had the lowest values of these traits, the plant height, dry weight/plant, leaf area index, total chlorophyll, yield, and yield components—such as spike length, number of spikes/m2, number of grains/spike, 100-grain weight, grain yield, biological yield and harvest index, and chemical composition—such as nitrogen, phosphorus, potassium, and protein percentages—were significantly increased. Plant height, dry weight/plant, leaf area index (LAI), total chlorophyll (SPAD), spike length, number of spikes/m2, number of grains/spike, 100-grain weight, grain yield, biological yield and harvest index, and chemical composition (nitrogen, phosphorus, potassium, and protein percentages) on wheat cv were all significantly impacted by the interaction of irrigation levels, mycorrhizal inoculation, and compost tea. "Sakha 93"

Keywords: Wheat (Triticum aestivum L.), water stress, mycorrhizae, compost tea, growth, yield and yield components, chemical composition.

الملخص
أُجريت هذه التجربة في منطقة اولاد علي بمزرعة الباحث موسى محمد إبراهيم مدينة ترهونة ، ليبيا، خلال موسم الشتاء 2025/2024. هدفت هذه الدراسة إلى دراسة تأثير الري بثلاثة مستويات (100، 75، 50%)، والتلقيح بفطر الميكوريزا (AMF) مع شاي السماد (CT) بمعدلات (15، 30،45 %) على محصول القمح صنف "سخا 93". نُفذت معاملات التجربة بتصميم القطع المنشقة، حيث تضمنت القطع الرئيسية على مستويات الري، والقطع تحت الفرعية تتضمن الميكوريزا + شاي الكمبوست، بثلاث مكررات لكل معاملة. أظهرت النتائج المتحصل عليها أن مستوى الري بنسبة 100% سجل أعلى قيم للنمو الخضري أي ارتفاع النبات والوزن الجاف/ نبات ومؤشر المساحة الورقية والكلوروفيل الكلي والمحصول ومكوناته أي طول السنبلة وعدد السنابل/ م2 وعدد الحبوب/سنبلة ووزن 100 حبة ومحصول الحبوب والمحصول البيولوجي ومؤشر الحصاد والتركيب الكيميائي أي النسب المئوية النيتروجين والفوسفور والبوتاسيوم والبروتين، مقارنة بمعاملة الكنترول التي سجلت أقل قيمة لهذه الصفات. من ناحية أخرى، أدت الفطريات الجذرية (AMF) + شاي الكمبوست عند التركيز المرتفع (45 مل / لتر) إلى زيادة معنوية في ارتفاع النبات والوزن الجاف / نبات ومؤشر مساحة الورقة والكلوروفيل الكلي والمحصول ومكوناته أي طول السنبلة وعدد السنابل/ م2 وعدد الحبوب / سنبلة ووزن 100 حبة والمحصول ومكوناته والمحصول البيولوجي ومؤشر الحصاد والتركيب الكيميائي أي نسب النيتروجين والفوسفور والبوتاسيوم والبروتين، مقارنة بمعاملة الكنترول التي سجلت أقل قيمة لهذه الصفات. من ناحية أخرى، ساهمت فطر الميكوريزا مع شاي الكمبوست بالتركيز العالي (45 مل/لتر) في زيادة معنوية لارتفاع النبات، والوزن الجاف للنبات، ومؤشر مساحة الورقة، والكلوروفيل الكلي، والمحصول ومكوناته (طول السنبلة، وعدد السنابل/م^2، وعدد الحبوب/سنبلة، ووزن 100 حبة، ومحصول الحبوب، والمحصول البيولوجية، ومؤشر الحصاد، والتركيب الكيميائي (نسب النيتروجين والفوسفور والبوتاسيوم والبروتين) على صنف القمح "سخا 93". كان للتفاعل بين مستويات الري، وتلقيح فطر الميكوريزا مع شاي الكمبوست تأثير معنوي على ارتفاع النبات، والوزن الجاف للنبات، ومؤشر مساحة الورقة، والكلوروفيل الكلي (SPAD)، وطول السنبلة، وعدد السنابل/م^2، وعدد الحبوب/سنبلة، ووزن 100 حبة، ومحصول الحبوب، والمحصول البيولوجي، ومؤشر الحصاد، والتركيب الكيميائي (النسب المئوية للنيتروجين والفوسفور والبوتاسيوم والبروتين).

الكلمات المفتاحية: القمح (Triticum aestivum)، الإجهاد المائي، الميكوريزا، شاي الكمبوست ، النمو، المحصول ومكونات المحصول، التركيب الكيميائي.

INTRODUCTION

Wheat (*Triticum aestivum* L.) remains one of the world's most vital cereal crops, providing a major share of daily caloric and protein intake for millions of people. As global population growth continues and food demand intensifies, enhancing wheat productivity under changing environmental conditions has become a central challenge for agricultural systems worldwide. Among the most critical pressures limiting wheat performance is water scarcity, a constraint that is expected to intensify under future climate scenarios. Reduced water availability disrupts photosynthesis, nutrient uptake, biomass accumulation, grain development, and ultimately yield. Consequently, developing sustainable strategies to mitigate water stress effects is essential for maintaining crop productivity and ensuring food security.

In recent years, biological approaches—particularly the use of arbuscular mycorrhizal fungi (AMF) and compost tea (CT)—have gained attention as promising tools for improving plant tolerance to abiotic stress. AMF form symbiotic associations with plant roots, enhancing water absorption, improving nutrient availability, stabilizing soil structure, and stimulating physiological mechanisms that support growth under drought conditions. Similarly, compost tea is rich in beneficial microorganisms and bioactive compounds that enhance soil fertility, promote nutrient cycling, stimulate root development, and strengthen plant resilience. When combined, AMF and compost tea may offer synergistic benefits that improve both vegetative growth and yield components, especially under limited irrigation.

The integration of these biostimulants aligns with modern sustainability approaches, which seek to reduce reliance on chemical fertilizers and enhance soil health through environmentally friendly practices. However, despite growing evidence supporting their individual benefits, limited research has examined their combined effects on wheat under varying levels of water stress. This knowledge gap is particularly relevant for semi-arid regions such as Libya, where agricultural production is frequently constrained by drought, poor soil fertility, and inefficient water use.

Therefore, the present study aims to evaluate the effects of different irrigation levels and combined AMF + compost tea inoculation rates on the growth, yield, and chemical composition of wheat cultivar "Sakha 93." By assessing plant responses across multiple physiological and agronomic parameters, this research seeks to clarify the potential of biological amendments in improving wheat performance under water-limited conditions. The findings are expected to contribute valuable insights toward promoting sustainable wheat production practices in arid and semi-arid environments.

lITERATURE REVIEW

Wheat will remain crucial to global food security because of the predicted increase in the world's population from 7.7 billion to 9.7 billion by 2050. It supplies 40% of the world's population's primary diet and feeds more than 4.5 billion people in 94 countries. It has 21% protein and 21% calories. Climate change may increase the frequency and severity of waterlogging stress, which is a major problem for wheat growing. Reducing the negative impact of waterlogging stress on wheat output was the aim of the raised bed planting scheme **(Chhabra *et al.,* 2025).**

Wheat, a significant grain crop farmed worldwide, is a member of the Poaceae family. Wheat is a staple cereal grain for the great majority of people on the earth. It has 8–20% protein and 17–21% calories globally. Population growth has led to a greater need for food production, especially for cereals. By 2050, grain production is predicted to increase by 60% worldwide **(Asseng, 2020; Du, 2021).** One of the most important cereal crops grown globally is wheat. Wheat accounts for 30% of overall production and 50% of the world's grain trade. Furthermore, wheat is considered a staple grain in more than 40 nations worldwide. Because of its high nutritional content and versatility, wheat is the main food supply for over one-third of the world's population **(Kaur *et al.,* 2024).**

About 55% of the food's carbohydrates and 20% of its calories come from wheat. Significant amounts of minerals (zinc and iron), vitamins (thiamine and vitamin B), carbs (78.10%), protein (14.70%), and fat (2.10%) are all present. Magnesium, selenium, and other trace elements are abundant in wheat. Approximately 218.5 million hectares of land are used for wheat cultivation worldwide **(Kumar *et al.,* 2022).** Wheat is a globally significant cereal crop that significantly contributes to food and nutrition security. With 38.7% of the cropland utilized for rice, corn, and wheat, it is a cornerstone of global agriculture **(Yan *et al.,* 2022).** Its protein content is higher than that of usual animal sources, demonstrating its nutritional importance **(Elshamly and Abaza, 2024).**

The Mediterranean region places a lot of emphasis on the production and growth of wheat because it is the most significant, nutrient-dense, extensively grown, and most consumed crop in the world **(Arzani and Ashraf, 2017; Shaukat *et al.,* 2024 and Lamlom *et al.,* 2023, 2025).** It contains 2.5% fat, 69% carbs, 9.4% protein, and 1.8% fiber **(Ahmad *et al.,* 2022).** The importance of the wheat crop is further increased by the expanding population's requirement for food and nutrition **(Solangi *et al.,* 2021).** The livestock and animal feed sectors, which have great historical and cultural significance, also benefit greatly from it **(Nyaupane *et al.,* 2024).**

Cereals are vital for providing energy and nutrition to individuals worldwide, particularly to those residing in rural areas **(Sharma *et al.,* 2024a,b).** The most widely grown and produced crop is wheat, which is followed by corn, rice, and barley **(Sharma *et al.,* 2023; Liang *et al.,* 2024).** For around one-third of the world's population, wheat serves as their main food supply **(Nkebiwe *et al.,* 2024).** It has been essential to the shift to agriculture and the significant advancements in civilization, claim **Nkebiwe *et al.* (2024). Fazily *et al.* (2021)** claim that it provides a substantial amount of energy and is high in carbohydrates, particularly starch. In addition, wheat provides essential minerals and vitamins, such as iron, magnesium, phosphorus, zinc, and B-complex vitamins, as well as proteins and dietary fiber **(Kurylenko *et al.,* 2021; Jangir *et al.,* 2024).** However, **Hlisnikovský *et al.* (2023)** state that weather (temperature and precipitation) and fertilizer application are two significant factors that significantly affect wheat grain output and quality. One of the three major food crops in the world, wheat is essential to preserving human nutritional security and well-being **(Li *et al.,* 2020).** Wheat is a significant cereal crop that is necessary for the food and nutritional security of the world. For this reason, the crop's nutrient management strategy is essential **(Singh *et al.,* 2025).**

"One of the most widely farmed crops in the world, wheat, requires adequate fertilization to maintain high yields and grain quality". Additionally, it is nutrient-demanding and could contribute to soil exhaustion **(Fasani *et al.,* 2025).**

"Poor water utilization is a major issue because agriculture uses 76% of the nation's water and two-thirds of the country is dry or semi-arid"."Farmers frequently report crop losses due to droughts and other climate-related"challenges; many aquifers are overused or have problems like salinity and seawater intrusion **(Ochoa-Noriega *et al.,* 2020).**

"Water scarcity is one of the most common types of stress that limit crop yield, causing developmental delays and reductions in plant biomass"**(Ma *et al.,* 2024). Nyaupane *et al.* (2024)**"state that decreased rhizosphere water availability, increased transpiration rates, increased formation of reactive oxygen species"(ROS),"and the resulting induction of oxidative stress are the primary causes of water stress in plants. According to **Guo *et al.* (2024),** AMF can help their host withstand, manage, and recover from drought".

Drought is a significant environmental stressor that poses a global threat to wheat yield. It is predicted that the precipitation regime will alter and the frequency of dry spells will increase as the global climate changes. AMFs help wheat become more drought-tolerant and may even increase yield by changing the physiological and biochemical properties of the plant. **Emek and Yavas, (1921).** The extensive water absorption by extraradical hyphae, which enhances soil structure by creating a network rich in glomalin **(Nader *et al.,* 2024),** is one way mycorrhizae resist the effects of various stressors; however, little is known about these mechanisms **(Lenoir *et al.,* 2016).** Another indicator of a plant's increased capability for photosynthetic activity"is the increase in water vapor stomatal conductance, which gauges the rate of transpiration and CO_2 input"**(Peng *et al.,* 2024).**"Indirect mechanisms mediated by changes in the nutrition of the mycorrhizal plant are also mentioned"**(Guo *et al.,* 2024).**"AMF reportedly provides better protection against oxidative damage as well"**(Huang *et al.,* 2024).**"Mycorrhizal symbiosis improves gas exchange, stomatal conductance, transpiration, photosynthetic rates, and leaf water potential in plants under drought stress"**(Gholamhoseini *et al.,* 2013).**

Irrigation is the only method of human intervention that may increase soil moisture **(Ebmeyer *et al.,* 2021)** and has a significant effect on grain-filling and wheat yield formation **(Yan *et al.,* 2019).** Previous studies have shown that excessive or insufficient irrigation can lead to a considerable loss of productivity **(Yan *et al.,* 2022; Hamani *et al.,* 2023).** Excessive water inhibits source-sink conversion by encouraging rapid vegetative growth, which lowers grain-filling rate. However, water deficit during the early-filling stage limits the grain sink capacity by decreasing amyloplast development and endosperm cell division **(Abid *et al.,* 2017).**

In the face of global water shortage, effective water management in agriculture has become a crucial concern due to rapid population growth, urbanization, industrialization, and climate unpredictability. Agriculture accounts for about 70% of global freshwater withdrawal, highlighting the industry's critical role in preserving water resource sustainability **(Gebreel, 2020; Elsayed *et al.,* 2021)** and increasing irrigation water productivity to increase agricultural output while protecting freshwater resources for competing societal demands. Conventional surface irrigation methods dominate wheat production because they are inexpensive and simple to use.

However, evaporation and runoff can cause up to 50% of water losses from these methods, making less water available for crop absorption. These methods are often inefficient **(Al-Ansari *et al.,* 2019).**

The stomata close and less CO_2 is absorbed when there is a shortage of water. Severe drought stress affects plant physiology and growth, resulting in significant output losses and a drop in quality, claim **Posta and Duc (2020).** Known as mycorrhiza, arbuscular mycorrhizal fungi (AMF) are a type of soil fungus that live alongside the roots of certain plants. Through a symbiotic relationship, the plant provides extra water and mineral compounds, and AMF takes up carbohydrates from the host plant. A plant's growth, reproductive potential, water content, nutrients, and resistance to environmental stressors are all enhanced by a mycorrhizal relationship, claims **Duc (2017).**

The symbiotic relationship between AMF and plants, which enhances plant water relations and drought responsiveness, is one of the adaptations that plants have evolved to cope with water stress. AMF also reduces groundwater contamination by reducing the use of chemical fertilizers and removing contaminants from soil and irrigation water **(Pavithra and Yapa, 2018).** Compost tea has well-established benefits for crop growth and soil health. However, its effectiveness depends on the brewing environment and the type of the feedstock **(Bonanomi *et al.,* 2025).**

This study aims to evaluate the effects of mycorrhizal (AMF) plus compost tea (CT) inoculation and irrigation levels on the growth, yield, and chemical composition of the wheat cultivar "Sakha 93" in light of the previously mentioned factors.

MATERIALS AND METHODS

This investigation was conducted at Praivte from the city of Tripoli, Libya, during the winter of 2024–2025. The objective of the current study was to ascertain the effects of irrigation levels, mycorrhizal (AMF), and compost tea (CT) inoculation on the growth, yield, and chemical composition of the wheat cultivar "Sakha 93."

Experimental design

The study was set up as a split-plot, with mycorrhizal (AMF) + compost tea (CT) inoculation as a subplot and irrigation levels as the main plot. There were three duplicates of each therapy.

Main plot (irrigation levels)

- 100%
- 75 %
- 50%

B) Sub-plot (mycorrhizal + compost tea)

- Control
- Myco. + 15 ml/l CT
- Myco. + 30 ml/l CT
- Myco. + 45 ml/l CT

Data recorded

A) Vegetative growth

- Plant height (cm).
- Dry weight (g)
- Leaf area (cm^2): Each plant had a leaf sample taken, and the dimensions of each sample were measured before LA was manually calculated. A flag leaf was placed on a planar page, and its length and broadest point were measured in order to achieve this **(Ahmed *et al.*, 2015).** After that, LA was calculated using the following formula:
  Leaf Area = (length x width) x correction factor (0.75)

Where the correction factor accounts for leaf shape **(Schrader *et al.*, 2021).**

- Total chlorophyll (SPAD): The chlorophyll meter (SPAD-502, Minolta Co., Japan) was used to measure the total chlorophyll index; according to **Yadava (1986),** an average of four measurements from various leaf locations was taken into consideration.

B) Yield and Yield Components

- **Spike length (cm):** Awns from randomly labeled spikes in the net plot were not included in the measurement, which was taken from the spike's base to its tip.
- **Number of spike/ m^2:** was determined by averaging the number of spikes per square meter that were retrieved from each plot.
- **Number of spikelet/ spike:** was determined by averaging the spikelet number of 10 randomly selected spikes from each plot.
- **1000 grain weight (g):** Using an electronic seed counter for counting and an electronic sensitive balance for weighing, the weight of 1000 kernels sampled from each net plot's grain yield was used to calculate the thousand grain weights. After that, the weight was changed to reflect the 12.5% moisture content.
- **Grain yield (ton/ha):** For each experimental unit, the grain yield is computed per square meter.
- **Biological yield (ton/ha):** Biological yield= Grain yield + straw yield (t/fed).
- **Harvest index (%):** the following formula is used to determine the harvest index for crop yield based on the means of grain yield and biological yield for each treatment **(Sharma and Smith, 1986):**

The harvest Index= Grain yield /Biological yield x100

C) Chemical composition

Grain samples from each treatment were gathered, and the N, P, and K percentages were determined. After that, the grains were crushed, dried, and put away for further analysis. 0.5 g of the grain powder was wet-digested using a mixture of H_2SO_4 and H_2O_2. Nessler's approach **(A.O.A.C., 1990)**"was used to calculate the calorimetric total nitrogen in digested plant matter"."Following the measurement at 420 nm, N was calculated using the following formula":

N % = NH4% × 0.78

"The protein content in the wheat grains was calculated using the Formula as follows":

Total protein = N content (%) × 6.25

Statistical analysis:

Following computerized statistical analysis of the measured parameters' results using SAS statistical software version 9.0 for analysis of variance (ANOVA), the means of the treatments were compared using LSD at 0.05, as per **Snedecor and Cochran (1990).**

RESULTS AND DISCUSSION

A) Vegetative growth

The results in **Table (1) and Figure (1)** showed how plant height, dry weight/plant, leaf area (LA), and total chlorophyll (SPAD) were affected by irrigation at three levels (100, 75, and 50%) and inoculation of Mycorrhizae (AMF) + compost tea (CT) at rates of 15, 30, and 45% during the 2024–2025 season. The plant height (119.67 cm), dry weight/plant (67.89 g), leaf area (6.75 cm^2), and total chlorophyll (41.27 SPAD) were all higher at the 100% irrigation level than at the control treatment, which showed lower values for plant height (112.44 cm), dry weight/plant (46.35 g), leaf area (4.25 cm^2), and total chlorophyll (28.66 SPAD). AMF+ compost tea at high level (45 ml/l) significantly increased plant height (125.65 cm), dry weight/plant (68.95 g), leaf area (7.39 cm^2), and total chlorophyll (43.33 SPAD) in contrast to the control treatment, which displayed lower plant height (109.09 cm), dry weight/plant (50.56 g), leaf area (4.38 cm^2), and total chlorophyll (27.08 SPAD). The combination of mycorrhizal inoculation, compost tea, and irrigation levels significantly affected plant height, dry weight/plant, leaf area and total chlorophyll (SPAD) on wheat cv. "Sakha 93" throughout the 2024–2025 growing season.

These results are consistent with those of **Shishehbor *et al.* (2013),** who discovered that mycorrhiza inoculation with vermicompost and Azotobacter greatly affected total dry matter. The total dry matter yield of maize was considerably raised by the *G. intraradices* inoculation. Similarly, compared to mycorrhiza non-inoculation and control treatments, mycorrhiza inoculation in conjunction with vermicompost or rhizobium produced the highest yield **(Mahesweri *et al.*, 2006).** Photosynthesis is significantly impacted by plant height. Water stress dramatically decreased the shoot length of guar genotypes, according to earlier research by **Malik and Hassan (2002).** When compared to irrigated wheat types, plant height dramatically decreased during water stress, according to **Inamullah *et al.* (1999).**

Utilizing AMF technology may be a sustainable way to enhance plant performance in challenging circumstances, as evidenced by the beneficial impacts of AMF on wheat growth under varying drought levels **(Malik *et al.*, 2017).** AM symbiosis enhances the water-plant relationship during drought stress, which can impact a number of physiological processes. It also promotes the expansion of leaf area and coarse root mass. The increased water intake can be the cause of the mycorrhizal plants' increased biomass **(Habibzadeh *et al.*, 2013). Omara *et al.* (2022)** found that foliar CT spraying improved rice growth at different irrigation intervals. Mycorrhiza fungal inoculation resulted in a comparatively large increase in plant height in the plants studied, according to **Copetta *et al.* (2006).** Additionally, these plants had improved general morphological traits in soybean plants.

Table (1): Impact of irrigation levels and Mycorrhizae (AMF) with compost tea inoculation on wheat cv. "Sakha 93" plant height, dry weight/plant, leaf area index, and total chlorophyll.

Treatments	Plant height (cm)	Dry weight/ plant (g)	Leaf area (cm^2)	Total chlorophyll (SPAD)

A) Irrigation levels				
100%	119.67	67.89	6.75	41.27
75%	116.56	58.64	5.88	34.96
50%	112.44	46.35	4.25	28.66
LSD$_{(0.05)}$	**0.83**	**3.65**	**3.56**	**5.30**
B) Myco+ Compost tea				
Control	109.09	50.56	4.38	27.08
Myco+ Compost tea at 15 ml/l	121.21	55.31	5.65	30.09
Myco+ Compost tea at 30 ml/l	123.44	64.25	6.7	36.71
Myco+ Compost tea at 45 ml/l	125.65	68.95	7.39	43.33
LSD$_{(0.05)}$	**0.87**	**6.58**	**4.1**	**5.57**
(A×B)	*	*	*	*

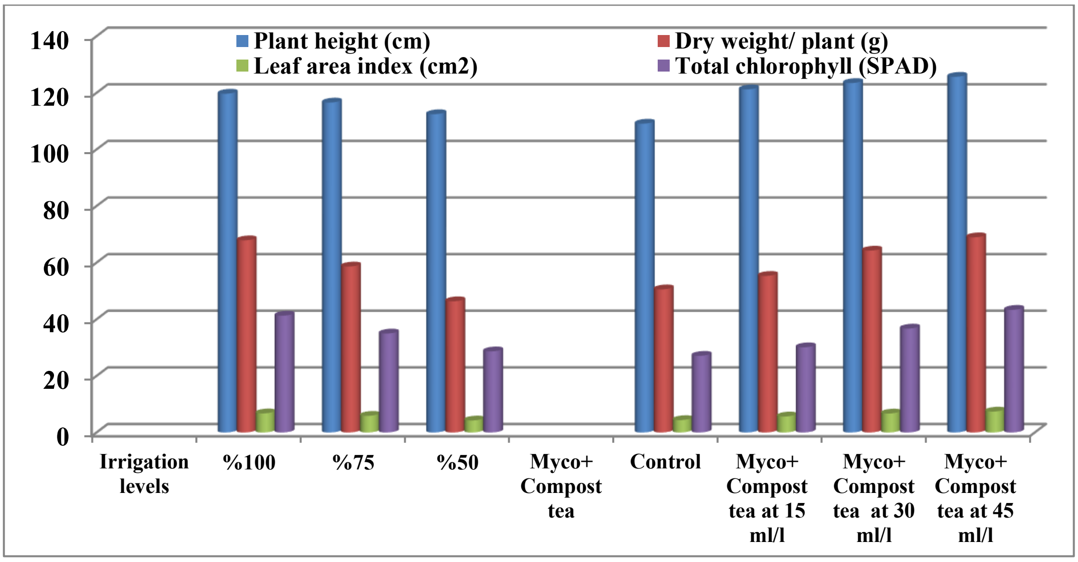

Figure (1): Impact of irrigation levels and Mycorrhizae (AMF) with compost tea inoculation on wheat cv. "Sakha 93" plant height, dry weight/plant, leaf area index, and total chlorophyll.

B) Yield and yield components

During the 2024–2025 season, the results in **Table (2) and Figure (2)** showed the effects of irrigation at three different levels (100, 75, and 50%) and mycorrhizae (AMF) plus compost tea (CT) inoculation at rates of 15, 30, and 45% on spike length, number of spikes/m2, number of grains/spike, 100-grain weight, grain yield, biological yield, and harvest index. The 100%

irrigation level recorded higher values for spike length (10.79 cm), number of spike/m2 (458.33), number of grains/spike (56.31), 100-grain weigh (45.43 g)t, grain yield (3.28 t/ha), biological yield (7.33 t/ha), and harvest index (44.75%) than the 50% treatment, which recorded lower values for spike length (9.80 cm), number of spike/m^2 (358.25), number of grains/spike (43.27), 100-grain weigh (31.99g), grain yield (2.65 t/ha), and biological yield (4.20 t/ha). AMF+ compost tea at high level (45 ml/l) significantly increased the following: spike length (11.00 cm), number of spike/m2 (520.73), number of grains/spike (57.43), 100-grain weigh (46.82g), grain yield (3.57 t/ha), and biological yield (9.75 t/ha) in comparison to the control treatment, which recorded the lower spike length (9.55 cm), number of spike/m2 (264.33), number of grains/spike (41.74), 100-grain weigh (34.13 g), grain yield (2.92 t/ha), biological yield (6.43 t/ha), and harvest index (45.41%). The 2024–2025 season had significant effects on spike length, number of spikes/m2, number of grains/spike, 100-grain weight, grain yield, biological yield, and harvest index on wheat cv. "Sakha 93" due to the interplay of irrigation levels, mycorrhizal inoculation, and compost tea.

Therefore, it is imperative that these natural and biological resources be exploited sustainably. After using the studied fertilization systems, spike production and number of spikes/ m^2 may increase as a result of improved nutrient uptake, decreased leaching losses, and increased biological activity **(Agamy *et al.,* 2012).** Grain yield, plant height, and the number of tillers may have all contributed to this increase in biological output. These findings concur with **EL-Guibali's (2016)** findings. This advantage may be attributed to the higher assimilate content of these varieties, which increased the amount of dry matter deposited and, consequently, the number of spikes and grains as well as the grain weight. **Abd El-Kreem and Ahmed (2013) and Osman and Nor Eldein (2017)** revealed significant differences across wheat varieties in terms of spike weight, 1000-grain weight, and/or number of grains/spike. This implies that compared to the other kinds under investigation, Giza 171 has a greater capacity for photo-assimilate transfer to sinks (grains). These findings align with those of **El-Seidy and colleagues (2017).** The quantity of grains per spike is significantly reduced by water stress **(Tompkins *et al.,* 1991).** Water stress during vegetative and reproductive development has been shown to significantly reduce the number of grains per spike in wheat **(Khanzada *et al.,* 2001a; Qadir *et al.,* 1999).**

These findings are in line with those of **Khan *et al.* (2005),** who found that rising water stress was the main cause of the decline in wheat's 1000-grain weight. Increased photosynthetic pigments may be the cause of the increases in grain weight and/or quantity. In contrast to conventional irrigation, a number of researchers found that spike attributes were enhanced by irrigation employing bed systems **(El-Seidy *et al.,* 2015)** and gated pipes **(Kumar *et al.,* 2023).** The flow of photoassimilate from vegetative tissues to grains, which encourages cell division and the accumulation of storage capacity, is strongly influenced by the nutritional state of plants **(Mendel and Kirkby, 2001). Mandic *et al.* (2015)** found that the use of several fertilizers was associated with increases in 1000 grain weight and spike weight.

Similar results were noted by **Pezeshkpour *et al.* (2014),** who contended that mycorrhiza fungal inoculation had a greater impact on grain yield than vermicompost and bacterial treatment. Similarly, **Shishehbor *et al.* (2013)** demonstrated that the combination of vermicompost with Azotobactor greatly enhanced grain yield. The treatments that used Azotobactor and vermicompost produced the most grain. The mycorrhiza fungus increases the accessibility of nutrients in vermicompost, which aids in plant growth and increased yield. Plants then progressively absorb these nutrients. Consequently, the weight of the grains

increased when mycorrhiza and vermicompost were applied. When compared to the control treatment, the inoculation of vermicompost and Azotobacter mycorrhiza considerably increased the hundred grain weight **(Shishehbor *et al.*, 2013).**
In many parts of the world, especially in arid and semi-arid countries, water scarcity significantly hinders the production of agricultural and horticultural crops **(Jia *et al.*, 2017).** According to **Helaly *et al.* (2017),** plants require water in order to grow, develop, and produce seeds. When water is low, wheat exhibits decreased harvest index, number of spikes per unit area, number of spikelets per spike, 1000-seed weight, biological yield, grain yield, and number of seeds per spikelet **(Allahverdiyev *et al.*, 2018).** A water deficiency also reduces the dry weight of leaves and stems and the pace of grain filling **(Selim et al., 2019).**

Table (2): Impact of mycorrhizal (AMF) inoculation and irrigation levels on wheat cv. "Sakha 93" production and yield components.

Treatments	Spike length (cm)	No. of spike/ m^2	No. of grain/ spike	100-grain weight (g)	Grain yield (t/ha)	Biological yield (t/ha)	Harvest index (%)
A) Irrigation levels							
100%	10.79	458.33	56.31	45.43	3.28	7.33	44.75
75%	10.60	427.00	49.44	42.41	3.08	5.68	54.23
50%	9.80	358.25	43.27	31.99	2.65	4.20	63.10
$LSD_{(0.05)}$	**0.08**	**8.70**	**2.30**	**1.35**	**0.12**	**1.20**	**2.55**
B) Myco+ Compost tea							
Control	9.55	264.33	41.74	34.13	2.92	6.43	45.41
Myco+ Compost tea at 15 ml/l	10.33	379.00	47.17	37.72	3.30	7.80	42.31
Myco+ Compost tea at 30 ml/l	10.71	494.00	52.33	41.41	3.44	8.93	38.52
Myco+ Compost tea at 45 ml/l	11.00	520.73	57.43	46.82	3.57	9.75	36.62
$LSD_{(0.05)}$	**0.02**	**11.20**	**0.02**	**1.50**	**0.13**	**0.52**	**2.51**
(A×B)	*	*	*	*	*	*	*

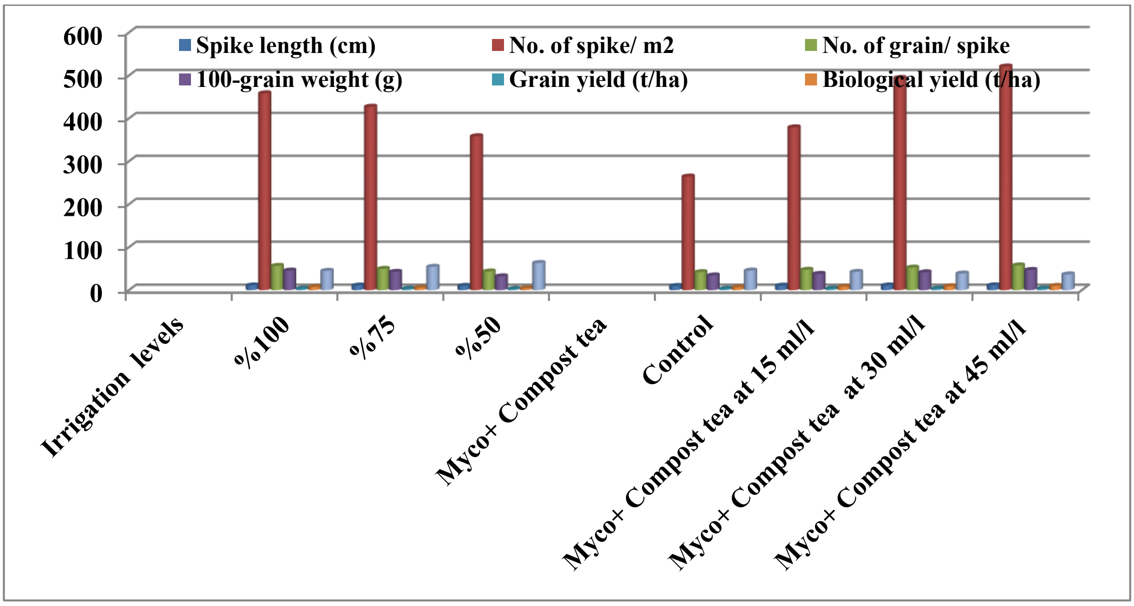

Figure (2): Impact of mycorrhizal (AMF) inoculation and irrigation levels on wheat cv. "Sakha 93" production and yield components.

C) Chemical composition

The results in **Table (3) and Figure (3)** showed how the percentages of nitrogen, phosphate, potassium, and protein changed during the 2024–2025 season as a result of irrigation at three levels (100, 75, and 50%) and mycorrhizae (AMF) with compost tea (CT) inoculation at rates (15, 30, and 45%). However, the 100% irrigation level recorded greater quantities of nitrogen (1.82%), phosphorus (0.228%), potassium (3.53%), and protein (11.38%) than the 50% treatment irrigation level, which recorded lower nitrogen, 1.54%, phosphorus, 0.208, potassium, and protein, respectively. AMF+ compost tea at a high level (45 ml/l) markedly increased nitrogen (1.94%), phosphorus (0.397%), potassium (4.93%), and protein (12.13%) compared to the control treatment, which showed lower levels of nitrogen (1.27%), phosphorus (0.220%), potassium (3.45%), and protein (8.94%), respectively. Compost tea, mycorrhizal inoculation, and irrigation levels all had a significant effect on the percentages of nitrogen, phosphate, potassium, and protein on wheat cultivar "Sakha 93" during the 2024–2025 growing season.

An *et al.* (2019) claim that AMF and their host plants form a symbiotic relationship in which they trade carbon sources like sugars and lipids for water and nutrients. AMF dramatically boosts drought-stricken plants' uptake of phosphorus (P) and nitrogen (N) **(Tang *et al.*, 2022).** *Rhizophagus irregularis* inoculation tests have shown that even mild drought stress significantly raises plant leaf P and Ca (calcium) levels **(Li *et al.*, 2021).**

According to **Metwally *et al.* (2019),** AMF interventions have also been demonstrated to improve the water status of crops such as wheat, which in turn promotes the synthesis of chlorophyll during drought circumstances, ultimately resulting in higher yields and growth.

According to **Adhikary (2012),** the use of vermicompost in conjunction with fertilizers significantly increased the uptake of nitrogen by plants as well as the uptake of macronutrients such as N and P. Arbuscular mycorrhizal fungal hyphae are primarily involved in the absorption and assimilation of ammonium (NH_4^+). Arbuscular mycorrhizae (AM) establish symbiotic relationships between fungi and plant roots, which are essential for improving nutrient uptake and micronutrient solubility, particularly when paired with organic substrates

(Khan *et al.*, 2022). It has been demonstrated that inoculating wheat with arbuscular mycorrhizal fungus (AMF) spores increases root density and phosphate absorption **(Hazzoumi *et al.*, 2022).** Moreover, long-term fertilization techniques significantly impact AMF population dynamics in agricultural environments **(Ma *et al.*, 2021).**
AMF is especially good at mobilizing immobile phosphorus in calcareous soils, which increases grain productivity **(Wahid *et al.*, 2020).** AMF also increases alkaline phosphatase activity and microbial diversity, which increases the amount of organic phosphorus available **(Fall *et al.*, 2022).** The advantages of AMF inoculation, an environmentally safe method of increasing soil fertility and crop productivity **(Dal Cortivo *et al.*, 2018),** are greatly increased when combined with compost treatment **(Xin *et al.*, 2022).** Compost increases the amount of N that is inoculated into the soil by AMF. AMF impacts the nitrogen, carbon, and phosphorus cycles as well as soil nutrients **(Parihar *et al.*, 2020; Farrag and Bakr, 2021).**
Chemical fertilizers and municipal compost enhanced the crop's nitrogen status, allowing it to employ ingested nutrients more effectively **(Muchhadiya *et al.*, 2021).** In order to help plants grow, mycorrhizal fungi are essential for feeding and watering them **(Manoj *et al.*, 2022).** For certain essential elements for plants, such as phosphorus (P), nitrogen (N), sulfur (S), zinc (Zn), calcium (Ca), manganese (Mn), copper (Cu), magnesium (Mg), iron (Fe), and potassium (K), these fungi greatly enhance and boost the efficiency of plant absorption of nutrients in poor soil. The amount of these elements taken by the roots of plants connected with mycorrhizal fungi has increased, as evidenced by several studies that indicate higher concentrations of these nutrients in plants associated with AMF than in plants without AMF **(Moiseev, 2023).**

Table (3): Impact of irrigation levels and mycorrhizal (AMF) inoculation along with compost tea on wheat cv. "Sakha 93" protein, N, P, and K percentages.

Treatments	N (%)	P (%)	K (%)	Protein (%)
A) Irrigation levels				
100%	1.82	0.228	3.53	11.38
75%	1.70	0.219	2.78	10.63
50%	1.54	0.208	1.70	9.64
$LSD_{(0.05)}$	**0.06**	**0.04**	**0.45**	**1.7**
B) Myco+ Compost tea				
Control	1.27	0.220	3.45	8.94
Myco+ Compost tea at 15 ml/l	1.79	0.286	3.94	11.19
Myco+ Compost tea at 30 ml/l	1.86	0.345	4.52	11.63
Myco+ Compost tea at 45 ml/l	1.94	0.397	4.93	12.13
$LSD_{(0.05)}$	**0.04**	**0.002**	**0.64**	**2.09**
(A×B)	*	*	*	*

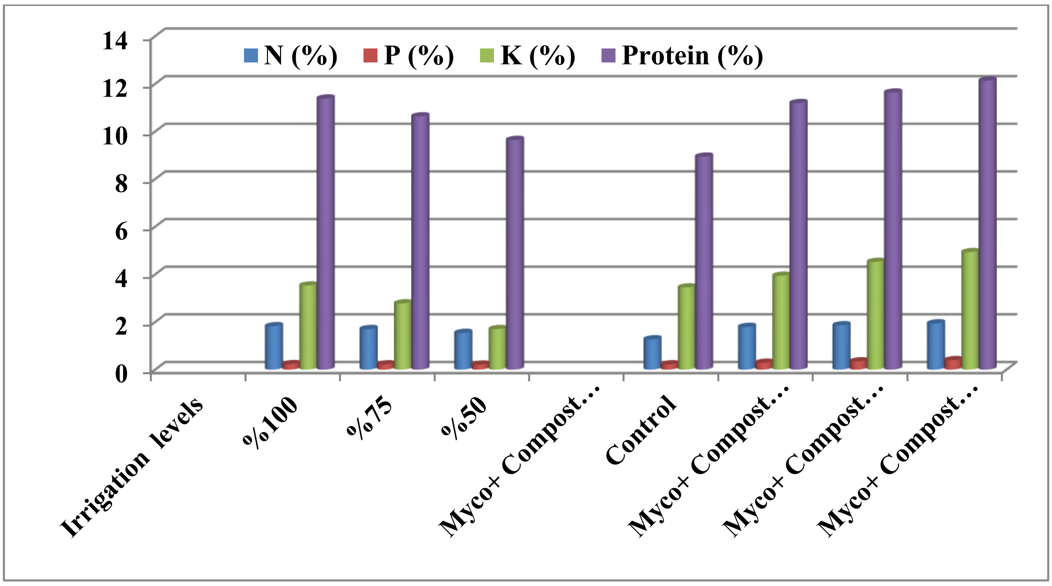

Figure (3): Impact of irrigation levels and mycorrhizal (AMF) inoculation along with compost tea on wheat cv. "Sakha 93" protein, N, P, and K percentages.

Conclusion

The findings of this study demonstrate that both irrigation level and the application of arbuscular mycorrhizal fungi (AMF) combined with compost tea (CT) exert significant and positive effects on the growth, yield, and chemical composition of wheat cultivar "Sakha 93." Across all measured parameters, plants receiving full irrigation (100%) consistently exhibited superior vegetative performance, higher chlorophyll content, enhanced yield attributes, and improved nutrient accumulation when compared with plants subjected to 75% and 50% irrigation. This confirms that water availability remains a primary determinant of wheat productivity, especially in semi-arid climates.

Equally important, the incorporation of AMF and compost tea—particularly at the highest concentration (45 ml/l)—resulted in notable improvements in plant height, dry matter accumulation, leaf area expansion, and chlorophyll content. These biological enhancements translated into significant increases in spike length, number of spikes per square meter, grain number per spike, 100-grain weight, grain yield, and biological yield. The combined treatment also improved nitrogen, phosphorus, potassium, and protein percentages, indicating more efficient nutrient uptake and assimilation. These results emphasize the synergistic role of AMF and compost tea in strengthening plant tolerance to water stress, improving root function, and boosting physiological activity even under reduced irrigation.

The significant interaction effects observed between irrigation levels and AMF + CT treatments highlight the potential of biological amendments to partially offset the negative impacts of water scarcity. In particular, the highest inoculation level under deficit irrigation achieved notable improvements, demonstrating that AMF and compost tea can serve as practical tools for enhancing resilience in water-limited environments.

Overall, this study supports the integration of AMF and compost tea as sustainable, eco-friendly strategies for improving wheat performance under drought conditions. Their adoption in arid and semi-arid regions, such as Libya, could contribute meaningfully to improved food production and long-term agricultural sustainability.

Recommendations

Based on the results obtained from evaluating the effects of irrigation levels and the combined application of arbuscular mycorrhizal fungi (AMF) with compost tea (CT) on wheat cultivar "Sakha 93," several recommendations can be proposed to enhance wheat production under water-limited conditions.

First, the integration of AMF and compost tea—especially at higher inoculation levels (45 ml/l)—is strongly recommended as a sustainable agricultural practice. This combination should be adopted by farmers in semi-arid regions, as it significantly improves vegetative growth, yield components, nutritional quality, and plant tolerance to drought. Extension programs should prioritize training farmers on the practical methods of preparing and applying compost tea, as well as the safe and effective use of AMF inoculants.

Second, full irrigation (100%) produced the highest yields; however, in areas where water availability is limited, applying a moderate irrigation level (75%) combined with AMF + CT inoculation can maintain respectable yields while conserving water. Therefore, policymakers and agricultural planners should consider promoting integrated water-saving strategies supported by biological amendments to increase water-use efficiency and reduce the negative impacts of drought.

Third, future research should explore long-term soil health improvements resulting from repeated AMF and compost tea applications. Studies on different wheat varieties, varying soil types, and broader geographic conditions are also encouraged to validate the generalizability of these findings. Additionally, further investigation into optimal microbial strains, compost formulations, and inoculation timing could help refine and enhance the effectiveness of these treatments.

Finally, since AMF and compost tea represent environmentally friendly alternatives to chemical fertilizers, their adoption supports sustainable agriculture and soil conservation. Thus, it is recommended that national agricultural programs and research centers integrate these biological inputs into extension packages designed to improve crop productivity while protecting natural resources.

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Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.