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# Impact of the Cultivation Methods and Irrigation Systems on Wheat Productivity and Carbon Footprint in Two Different Agro Ecological zones of Egypt

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***Abstract***— *Carbon footprint (CF) is one of the most important widely used indicators that quantify human use of natural resources and its emissions, where it can be used to guide policies to mitigate the stress of human activities on natural resources and the environment. Improving agricultural practices and systems may lead to mitigating greenhouse gas emissions. In this study the carbon footprint of wheat grown in various farming methods was ascertained in two different agro-ecological zones (Eastern desert and Sinai and Western desert and Oasis) in Egypt during the two growing seasons (2023-2024 and 2024-2025). The carbon footprint of wheat production was quantified based on the traditional practices data of the production process. The CF was found to be significantly different between both zones due to various cultivation systems, irrigation systems, fertilization, and pest control. The average carbon footprint differed between the two agro-ecological zones, irrigation systems and cultivation methods, ranging from 3088.9 to 3528.3 kg $CO_2$ eq./ha. The results also showed that there were significant differences in the impact of different farming methods and practices as well as irrigation systems on the carbon footprint rate, wheat yield and its components. The lowest carbon footprint values were recorded in the South Sinai region when using drip irrigation recorded 3088.9 kg $CO_2$ eq./ha, along with the highest water use efficiency 1.36 kg/m$^3$.*

***Keywords***— ***Carbon footprint, wheat, climate change.***

## I. INTRODUCTION

Increased global awareness of environmental challenges and their connections to social and economic difficulties has been a major driving force behind worldwide environmental legislation in recent decades. Global greenhouse gas (GHG) emissions must be significantly reduced, according to international accords and scientific evaluations. Where led to the Earth's climate changes quickly due in significant part to rising anthropogenic greenhouse gas emissions. Global climate change is a result of agricultural activities that produce greenhouse gases (GHGs) during crop cultivation, food processing, and product marketing. 23–30% of all human greenhouse gas emissions worldwide are caused by agricultural operations (**Tubiello *et al.*, 2013; IPCC, 2019**). Farmers and the public are pushing for the creation and implementation of practical solutions to lower greenhouse gas emissions from all agricultural sectors and activities. However, there is a lack of quantitative data regarding the methods and approaches that should be used to lower agricultural emissions as well as how crop yield might impact the level of greenhouse gas emissions (**Gan *et al.*, 2011 a**).

Both freshwater usage and global warming are significantly impacted by food production. The second largest sectoral GHG emitter is the agriculture, forest, and other land use sectors, which contributed 24% of the world's GHG emissions in 2010 (**Kashyap, & Agarwal, 2021**). According to FAO, in 2017 70% of freshwater withdrawals worldwide and 95% of water withdrawals in certain developing nations are attributed to agriculture, which is also the major user of freshwater. Given its limited water resources, Egypt's expanding population presents the dual problem of increasing food production while reducing the corresponding greenhouse gas emissions.

Millions of people consume wheat every day, making it one of the most popular food sources worldwide. Its agriculture and production, however, have negative climatic consequences. Through greenhouse gases from fuel, artificial fertilizers, and pesticides used in wheat production have a detrimental effect on climate change (**Gan *et al.*, 2014**). Although enhancing agricultural practices would reduce greenhouse gas emissions (**Gan *et al.*, 2011 b**), until now it is unknown whether adopting alternative farming practices such as cultivation methods and irrigation system will enhance wheat productivity and reduce pollution by carbon emissions.

One of the most significant and commonly used metrics for measuring how much natural resources are consumed by humans and the emissions they produce is the carbon footprint (CF), which may be used to inform policy to lessen the impact of human activity on the environment and natural resources. The management of farms can be guided by the carbon footprint as an indicator due to the growing environmental impact of food production (**Zhang *et al.*, 2017**). Therefore, evaluating the CF of agricultural output is necessary before investigating the best farming methods with reduced greenhouse gas emissions. **IPCC 2019** states that GHG emissions from agricultural production in agroecosystems come from a variety of agricultural activities, such as the use of fertilizers, pesticides, irrigation water, and fossil fuels, in addition to cultivated soils.

The term "carbon footprint" was first introduced in a pioneering academic paper by **Rees (1992)**, which also presented the concept of the "ecological footprint." In a subsequent study, **Wiedmann and Minx (2008)** explained how carbon footprints can be utilized to assess the impact of greenhouse gas (GHG) emissions on environmental sustainability. Also, they reported that a carbon footprint is a measure of the exclusive total amount of carbon dioxide emissions that is accumulated over the life stages of a product or is directly and indirectly caused by an activity (**Gan *et al.*, 2011 a**).

The purpose of this study was to examine how irrigation systems and traditional cultivation practices impact wheat productivity and carbon footprints across two distinct agroclimatic zones of Egypt.

## II. MATERIALS AND METHODS

**Study site descriptions.**

The first region is the El-Kharga oasis at New Valley, located in the southwestern part of the country, in the south of Egypt's Western Desert (part of the Sahara Desert) (25.52° N and 30.61° E). Which is located within the agroecological zone of the Western Sahara and the oases: This area depends on groundwater (non-renewable) and is characterized by sandy soil. The climate of Kharga Oasis is a hot, hyper-arid desert climate (Köppen BWh), with highs of 41°C in August and lows of 2°C in January. The temperature ranged from 52°C to 2°C, with a relative humidity of about 39%.

The second region is Al-Wadi village, Al-Tor city, South Sinai, Egypt (28.21089°N, 33.35450°E, at an elevation of 14 m above sea level). Which is located within the agroecological zone of the Eastern Desert and Sinai: it is mostly harsh arid environments, with agriculture activities in valleys and areas containing groundwater, especially in the South Sinai Peninsula. Its climate features a hot desert climate (Köppen BWh) with scorching summers, mild winters, and extremely low precipitation with an average annual rainfall of no more than 7 mm and an average temperature of 23.2°C. The temperature ranged from 35°C in summer to 13°C in winter, with a relative humidity ranging between 51-66 %.

*Table 1. Soil Physicochemical properties during the two growing seasons (2023-2024 and 2024-2025)*

| Season | Texture | EC (ppm) | pH | Available aions (ml/l) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Ca | Mg | Na | CO3 | HCO3 | Cl- | SO4 |
| New Vally | | | | | | | | | | |
| **2023-2024** | **Sandy** | 936 | 8.1 | 12.3 | 7.8 | 17.02 | 4.13 | 6.87 | 95.9 | 0.71 |
| **2024-2025** | | 922 | 8.3 | 13.1 | 8.1 | 16.68 | 4.37 | 6.53 | 93.4 | 0.67 |
| South Sinai | | | | | | | | | | |
| **2023-2024** | **Sandy** | 1466 | 8.2 | 7.95 | 8.78 | 19.91 | 3.1 | 2.66 | 21.2 | 12.48 |
| **2024-2025** | | 1394 | 8.2 | 7.93 | 8.70 | 19.71 | 2.9 | 2.62 | 20.6 | 12.42 |

**Data sources**

Data used in the calculation of carbon footprint was originated from a field experiments conducted during the two growing seasons 2023-2024 and 2024-2025 in two Agro-Ecological zone of Egypt (Western Sahara and the oases - Eastern Desert and Sinai).

**Field experiments and layout**

Consumption and yield data for the 2023-2024 and 2024-2025 wheat growing seasons were calculated using three different irrigation systems (flood, drip, and sprinkler) in the first region, and only two in the second region (drip and sprinkler). employing the two seeding methods (Broadcasting and by seed drill in rows) in the first region and (broadcasting and by handheld seeder in rows) in the second region, during the two growing seasons.

Six experimental fields were cultivated during two growing seasons 2023-2024 and 2024-2025: four in the New Valley (three fields sown broadcast under the three irrigation systems—flood, sprinkler, and drip—and one field sown using a seed drill under flood irrigation), and two fields in South Sinai (one sown using a planter under drip irrigation, and the other was sown by broadcast under sprinkler irrigation system).

**Carbon footprint calculating**

The carbon footprint assessment is based on calculating greenhouse gas emissions GHGs through various agricultural activities, from the use of energy in the production and use of agricultural machinery, synthetic fertilizers, and chemicals for crop protection such as herbicides, pesticides, and fungicides, to the direct use of fuel in agricultural operations according to guidelines for national greenhouse gas inventories IPCC 2006.

## III. RESULTS

The comparative effects of various irrigation systems and cultivation methods on plant height and spike length (cm) under two agro-ecological zones, which are summarized in figure 1 (a, b) for both growing seasons. The results indicated that there was a considerable effect on plant height and spike length due to the two irrigation systems and cultivation methods under both zones.

The results showed a significant effect of irrigation systems on plant height in the two study areas. Wheat plants under drip irrigation exhibited the highest plant heights, reaching 118.6 and 105.5 cm, and spike lengths of 11.9 and 11.2 cm in the first and second areas, respectively. Conversely, sprinkler irrigation resulted in reduced wheat plant heights and spike lengths, with plant heights decreasing to 112.3 and 96.5 cm and spike lengths reaching 11.5 and 10.2 cm in the two study areas. Comparing flood irrigation with both drip and sprinkler irrigation systems in the first area (Western Desert and Oases) revealed clear differences, recording the lowest values for spike length and plant height, recorded 110.6 and 10.5 cm (Fig. 1 A).

On the other hand, the cultivation method had different effects on plant height and spike length in the two study zones. In the first zone (Kharga Oasis in the New Valley), the average plant height was 112.55 cm, while in the second zone (El Tor in South Sinai), the average spike length was 11.3 cm. Although plants grown using the broadcast method reached a higher height of 113.8 cm compared to those grown using the seed drill in rows (111.3 cm) in the first zone, no difference was recorded in spike length (11.3 cm). Conversely, plants grown using the broadcast method recorded the lowest plant height and spike length (96.5 cm and 10.2 cm) compared to plants grown using the handheld seeder in rows in the second zone, recorded 105.5 cm and 11.2 cm (Fig. 1B).

In addition, in general there were significant differences between the two study zones, with wheat performance in the Western Desert and Oases region (El-Kharga Oasis - New Valley) outperforming that of the Eastern Desert and Sinai region (El-Tur - South Sinai), where plant height and spike length increased by 11.88% and 5.61%, respectively.

When comparing the effects of different irrigation systems and planting methods on the number of grains per spike and the thousand-grain weight (g), the results indicate a significant variation in both grains per spike and thousand-grain weight depending on the irrigation system and planting method. This variation also differed between the two study regions. Drip irrigation achieved the best thousand-grain weight in both regions, reaching 51.62 g and 50.47 g in the Western Desert and Oases region, and the Eastern Desert and Sinai region, respectively (fig. 2A). However, sprinkler irrigation yielded the best number of grains-per-spike values, recording 33.5 g and 28.2 g in the first and second regions, respectively (Fig. 2 A). On the other hand, although broadcasting cultivation resulted in the best number of grains-per-spike in both regions, mechanized methods achieved the best 1000-grain weight, recording 50.73 g when using a seed drill in the first region and 50.47 g when using a handheld seeder in the second region (Fig.2 B).

Furthermore, wheat performed better in the Western Desert and Oasis region than in the Eastern Desert and Sinai. In the first region, the plants were superior in the number of grains/spikes as well as the weight of 1000 grains the average number of grains per spike was 32.13 grains per spike, and the average weight of 1000 grains was 50.22 g; on the other side in the second region, the average number of grains per spike was 27.25 grains per spike, and the average weight of 1000 grains was 49.22 g.

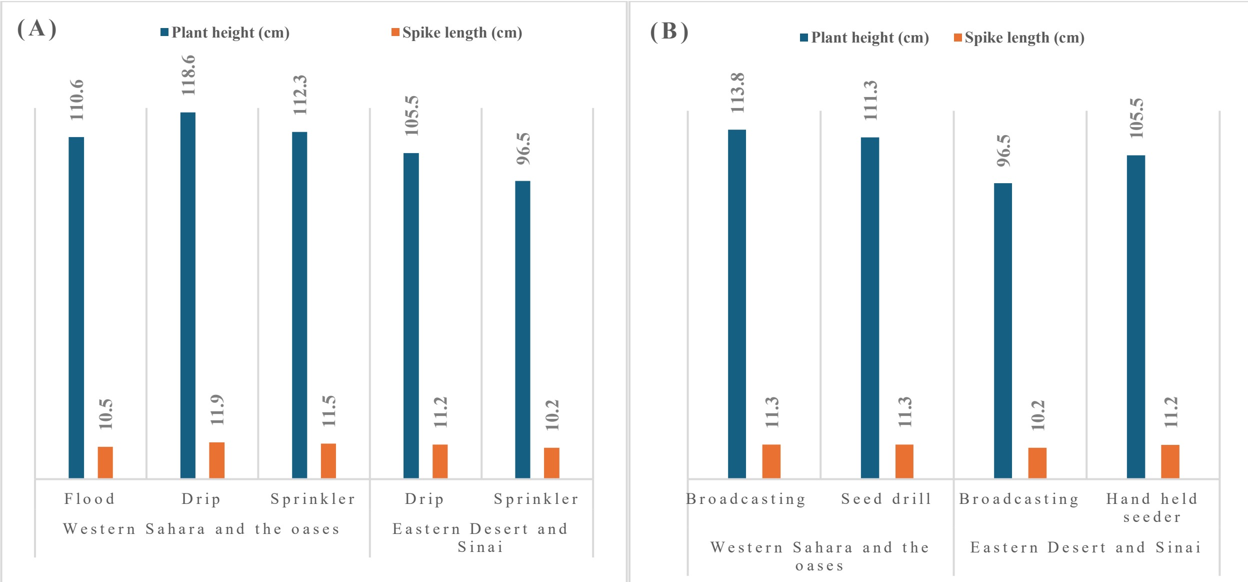


*Fig.1 Effect of irrigation system and cultivation methods on plant height and spike length (cm) of wheat under two agro-ecological zones conditions in Egypt*

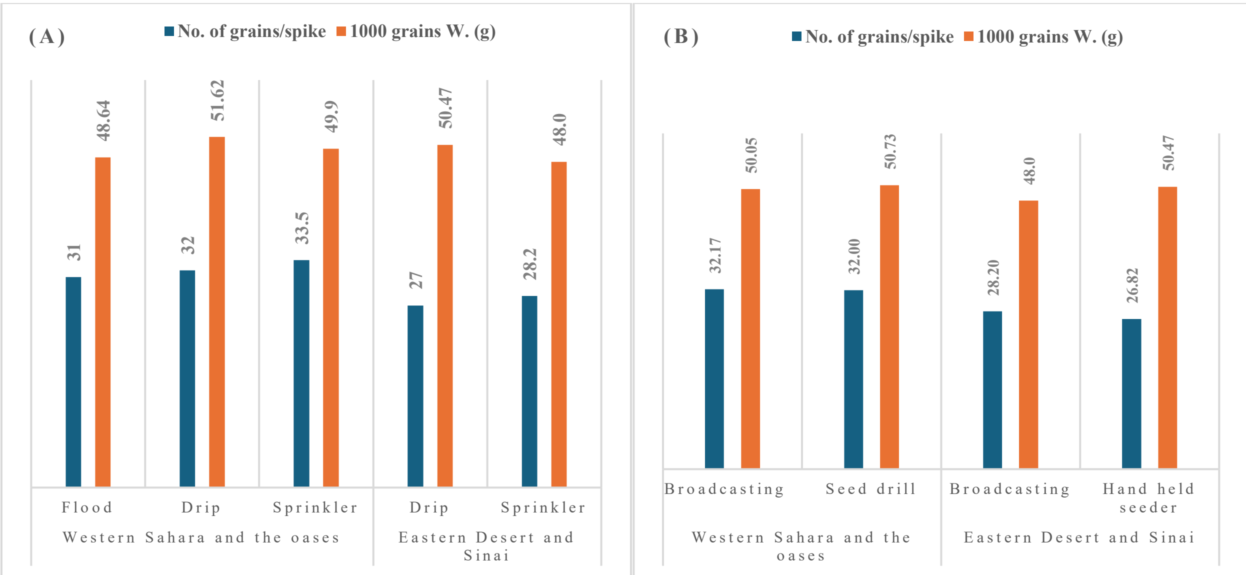


*Fig.2 Effect of irrigation system and cultivation methods on number of grains/spike and 1000 grains weight (g) of wheat under two agro-ecological zones conditions in Egypt*

The results in table 2. and figure 3. show that wheat productivity varied greatly between the two agricultural regions, with the Western Desert and Oases region (New Valley) outperforming the Eastern Desert and Sinai region (El-Tur) in both wheat productivity and biomass yield, achieving 7.62 t/ha and 28.72 t/ha, respectively. This indicates a 10.12% increase in grain yields and a 52.85% increase in biomass yields compared to the Eastern Desert and Sinai region. Regarding the irrigation systems used, drip irrigation achieved the best results in both study zones, with an average wheat yield of 8.25 t/ha in the New Valley, representing increases of 13.87% and 6.66% compared to flood and sprinkler irrigation systems, respectively. Biomass also increased by 14.62% and 29.31%, reaching 32.65 t/ha. Furthermore, average wheat yield and biomass under drip irrigation increased in the Eastern Desert and Sinai (El-Tur) regions, reaching 7.61 t/ha and 22.02 t/ha, respectively, representing increases of 22.15% and 41.52% compared to sprinkler irrigation. The study of planting methods effect revealed that mechanized planting systems are superior to manual broadcasting. Cultivation with a seed drill achieved the highest wheat yield and biomass, reaching 7.84 t/ha and 30.41 t/ha, respectively. This represents increases of 17.90% for grain yield and 14.50% for biomass in New Valley. Similar results were observed in El-Tur, where average yields with mechanized planting using a handheld seeder reached 7.61 t/ha, and the biomass yield was 22.02 t/ha. In contrast, the average wheat yield and biomass yield with broadcasting were 6.23 t/ha and 15.56 t/ha, respectively. These figures represent decreases of 18.13% and 29.34%, respectively, when compared to the results obtained from mechanized cultivation. According to the results in Fig. 3 (A and B) and Table 2, mechanized farming, utilizing either a seed drill or a handheld seeder within a drip irrigation system, achieved the highest levels of grain and biomass productivity across the two study zones, each characterized by different environmental conditions.

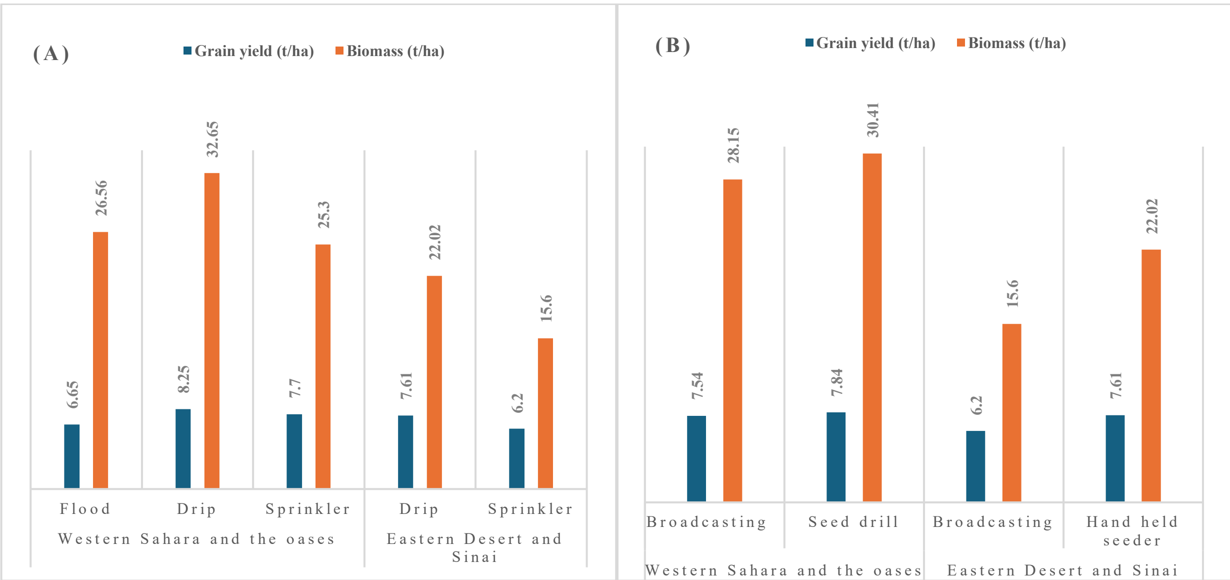


*Fig. 3 Effect of irrigation system and cultivation methods on grain yield and biomass of wheat (t/ha) under two agro-ecological zones conditions in Egypt*

The results in Table 2 and figure 4 (A and B) indicate significant differences in water use efficiency between the two agricultural environments zones studied. Water use efficiency ranged from 1.11 to 1.23 kg of grain per m³ of water in the Eastern Desert and Sinai (El-Tur), compared to the Western Desert and the oases (New Valley), respectively. The analysis revealed notable disparities in water use efficiency among the various irrigation systems. Flood irrigation exhibited the lowest efficiency, measuring at 0.87 kg of grain per m³ of water, while drip irrigation achieved the highest efficiency at 1.35 kg of grain per m³ of water, as well as sprinkler irrigation recorded a water use efficiency of 1.1 kg of grain per m³ of water. The results show that the best water use efficiency was achieved with mechanized planting using a handheld seeder under a drip irrigation system, reaching 1.36 kg grains/m³ water, while the lowest water use efficiency was recorded with broadcast planting and the application of a flood irrigation system, reaching 0.87 kg grains/m³ water.

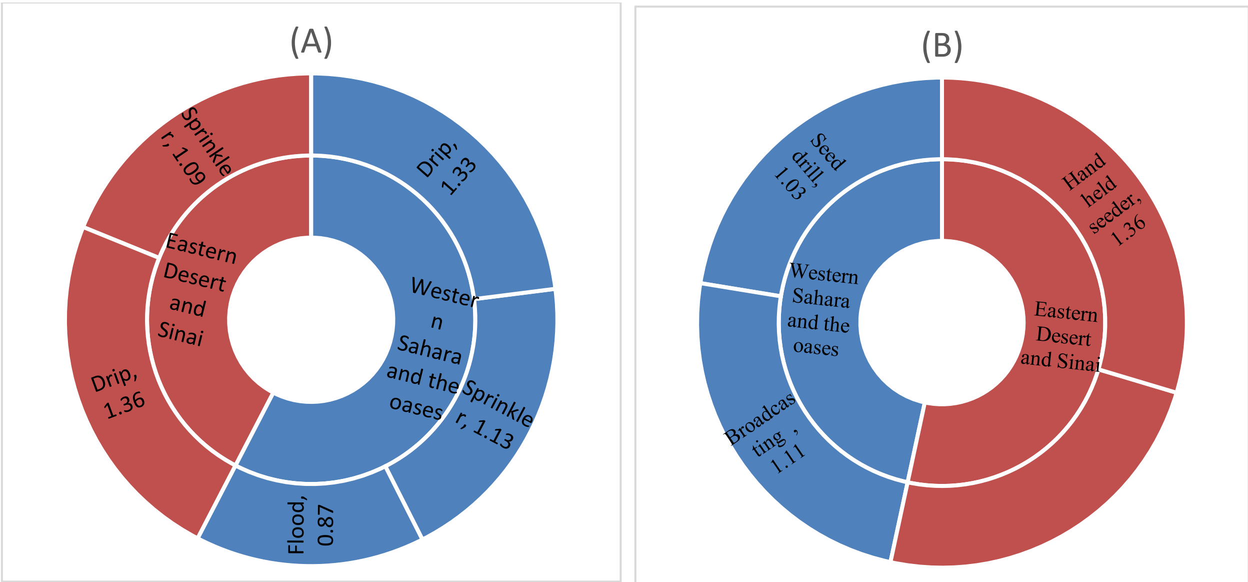


*Fig. 4 Effect of irrigation system and cultivation methods on water use efficiency (kg/m$^3$) in wheat fields under two agro-ecological zones conditions in Egypt.*

The estimation of $CO_2$ emissions in wheat production was based on the different methods and practices of wheat production in the selected zones. Throughout the many procedures seen throughout the survey, the evolution of operations farming practices considered tillage, cultivation methods, irrigation systems, plant protection, fertilizing, combine harvesting, and threshing as essential processes that contribute to the total carbon emissions in wheat production. By examining the inputs—such as labor, chemical fertilizers, seeds, herbicides, pesticides, and the efficiency of equipment sets used for tillage, harvesting, and threshing—the greenhouse gas emissions linked to these practices were determined. The information offered a thorough evaluation of the environmental effects of different wheat production systems, assisting in the identification of major sources of greenhouse gas emissions and providing information on possible areas where sustainable agriculture practices could be improved.

Data in figure 5 presents an assessment of greenhouse gas (GHG) emissions resulting from various farming practice inputs across different wheat production systems (cultivation methods and irrigation systems) in the two zones under study. The analysis clearly indicates that a drip irrigation system is associated with significantly lower GHG emissions compared to other systems (sprinklers or flood). Generally, the highest GHG emission was recorded in the second zone (Eastern Desert and Sinai) at 3528.3 kg $CO_2$-eq ha$^{-1}$ by the sprinkler irrigation system, whereas the lowest was observed in the drip irrigation system at 3088.9 kg $CO_2$-eq ha$^{-1}$.

Chemical fertilizers, such as urea, ammonium nitrate, and monocalcium superphosphate, are the main contributors to overall emissions across all treatments, according to a thorough analysis of emission sources. The second largest source is diesel fuel consumption, which is connected to the operation of machinery. Manure fertilizer comes next, followed by emissions from human labor, seed production, machinery use, and electricity. These results highlight how important farming techniques and nutrient management are to emission reduction plans. Potential approaches to reduce GHG emissions from wheat farming include increasing fertilizer application efficiency and implementing alternate fertilization processes. These findings support the wider use of sustainable farming practices to mitigate climate change issues while maintaining or increasing crop output.

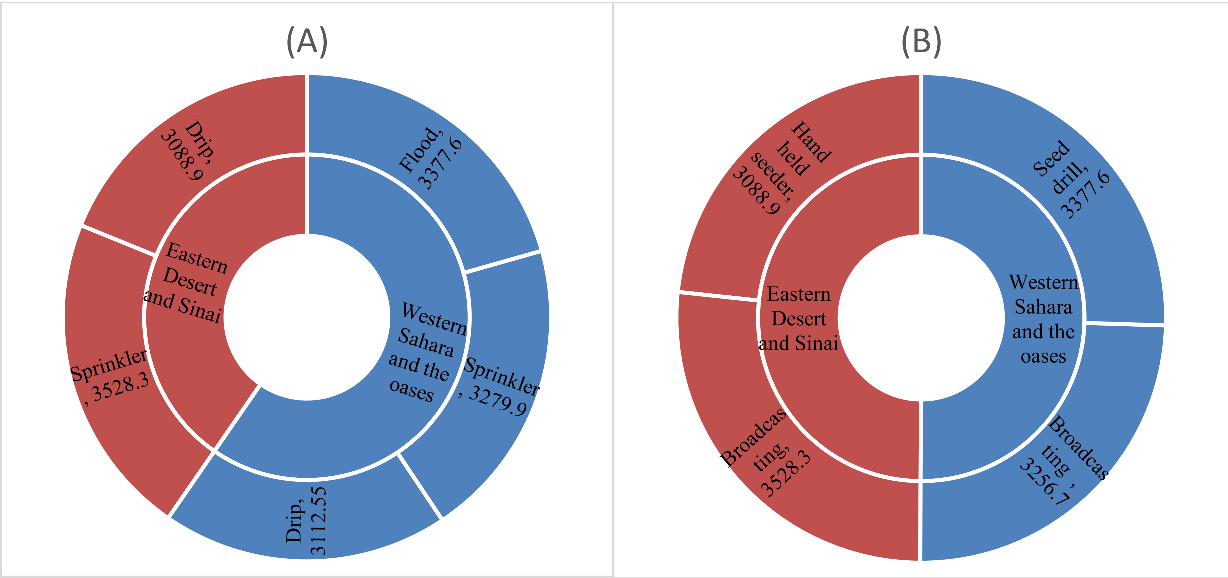


*Fig. 5 Effect of irrigation system and cultivation methods on carbon footprint in wheat fields under two agro-ecological zones conditions in Egypt.*

*Table 2. Impact of Irrigation Systems and Cultivation Methods on Wheat Performance in Two Agro-Ecological Zones of Egypt*

| Zone | Irrigation system | Cultivation methods | Sowing season | Grain yield (t/ha) | Biomass (t/ha) | Plant height (cm) | Spike length (cm) | No. of grains /spike | 1000 grains W. (gr) | WUE (Kg/m3) | Carbon footprint kg CO2 eq./ha |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Western Sahara and the oases | Flood | Broad casting | 2023-2024 | 6.43 | 25.66 | 105.6 | 9.6 | 33 | 48.19 | 0.84 | 3423.4 |
| | | | 2024-2025 | 6.87 | 27.46 | 115.5 | 11.3 | 29 | 49.08 | 0.90 | 3331.8 |
| | | Seed drill | 2023-2024 | 8.09 | 29.38 | 105.4 | 12.1 | 34 | 50.12 | 1.06 | 3390.4 |
| | | | 2024-2025 | 7.59 | 31.44 | 117.2 | 10.5 | 30 | 51.34 | 1.00 | 3364.8 |
| | Drip | Broad casting | 2023-2024 | 8.33 | 33.05 | 120.3 | 12.2 | 33 | 52.01 | 1.34 | 3126.4 |
| | | | 2024-2025 | 8.17 | 32.25 | 116.8 | 11.6 | 31 | 51.23 | 1.32 | 3098.7 |
| | Sprinkler | | 2023-2024 | 7.62 | 24.56 | 108.4 | 10.8 | 32 | 49.56 | 1.11 | 3310.3 |
| | | | 2024-2025 | 7.85 | 25.94 | 116.2 | 12.2 | 35 | 50.24 | 1.15 | 3249.5 |
| Eastern Desert and Sinai | Drip | handheld seeder | 2023-2024 | 7.78 | 22.13 | 108.5 | 11.6 | 26 | 51.07 | 1.40 | 3120.5 |
| | | | 2024-2025 | 7.43 | 21.91 | 102.4 | 10.8 | 27 | 49.87 | 1.32 | 3057.3 |
| | Sprinkler | Broad casting | 2023-2024 | 6.96 | 16.24 | 97.3 | 10.8 | 29 | 48.13 | 1.22 | 3580.2 |
| | | | 2024-2025 | 5.50 | 14.87 | 95.6 | 9.6 | 27 | 47.81 | 0.96 | 3476.4 |
| LSD $_{0.05}$ | | | | 0.22 | 1.11 | 0.89 | 0.43 | 2.33 | 0.87 | 0.67 | 36.38 |

## IV. DISCUSSION

**Gan *et al.* (2014)** demonstrated that adopting alternative agricultural practices will increase crop yields while reducing carbon emissions by integrating improved farming practices and implementing alternative wheat production systems better suited to semi-arid environments. The results indicate that integrating improved farming practices, particularly fertilizer application control, allows wheat to absorb more carbon dioxide from the atmosphere than it actually emits during its production. They also noted that weather significantly influences both carbon emissions and carbon sequestration, which accounts for the differences observed between the two study zones, due to the difference in climatic conditions between them. On the other hand, both Gan et al. (2009) and Campbell et al. (2000) stated that increased crop productivity under more favorable weather conditions leads to increased production of crop residues and root biomass, which helps to enhance soil organic carbon.

The study results showed a direct relationship between nitrogen fertilizer inputs and carbon emissions, with each kilogram of nitrogen generating approximately 8.5 kilograms of carbon dioxide equivalent per hectare of emissions. This was not surprising, as inorganic nitrogen fertilizers contributed the largest share of total emissions attributed to crop inputs. These findings are consistent with those of numerous studies conducted in arid wheat-producing regions, on the semiarid Canadian prairie by Gan *et al*. (2012); Rajaniemi *et al*. (2011) on oats, barley, spring wheat, and rye production in Finland; Brock *et al*. (2012) on wheat produced in the Central Zone (East) of New South Wales of Australia; Berry *et al*. (2010) on wheat in the United Kingdom; and Li *et al*. (2010) in China.

Irrigation is one land management technique that has a big impact on the environment, The findings demonstrated that implementing effective and low-carbon irrigation techniques can lower energy use and carbon emissions. These findings are in line with the findings of **Qin *et al***. (2024), who demonstrated that implementing highly effective and low-carbon irrigation techniques can cut energy use in half and carbon dioxide emissions by 90%. The findings indicate that energy consumption and carbon dioxide emissions can be significantly reduced when utilizing drip irrigation in conjunction with electric pumping. Therefore, when evaluating strategies to minimize energy use and carbon dioxide emissions, the feasibility of adopting drip irrigation becomes a critical consideration to reduce greenhouse gases as well as reduce the carbon footprint in wheat fields as outlined by **Qin *et al*., 2024**.

According to **Qin *et al***. (2024), two water-efficient irrigation methods are sprinkler and drip. Nevertheless, the findings demonstrate that sprinkler irrigation systems do not lower irrigation-related energy consumption and CO2 emissions worldwide and have greater energy and CO2 emissions intensity than surface irrigation. As a result, drip irrigation systems should be prioritized when deploying farm infrastructure, which is in line with the results of our study. **Huifang *et al***. (2021) found that drip irrigation led to reductions in carbon emissions, as well as water and energy usage, by 60%, 19.47%, and 45%, respectively, compared to traditional flood irrigation.

## V. CONCLUSION

The current study shows that while each farming technique has a unique impact on crop yield, combining those individually proven techniques in a methodical way can increase crop yield while also lowering the carbon footprint of crop production. In the field experiment, we identified and packaged a set of improved farming practices for spring wheat grown in two Egyptian agroecological zones: the eastern desert and Sinai (Al-tur) and the west desert and oasis (New Valley). These practices included (i) applying different irrigation systems and (ii) using different cultivation techniques. The results indicated that farming with a handheld seeder in conjunction with a drip irrigation system not only achieved the highest wheat productivity but also resulted in the lowest gas emissions and the lowest carbon footprint as well as the best water use efficiency.

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