Water-Energy Nexus 6 (2023) 122–130

Contents lists available at ScienceDirect

Water-Energy Nexus

journal homepage: www.keaipublishing.com/en/journals/water-energy-nexus/

On-farm water energy food carbon-footprint nexus index for quantitative assessment of integrated resources management for wheat farming in Egypt

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A R T I C L E   I N F O

Article history:
Received 16 February 2023
Revised 5 September 2023
Accepted 12 September 2023
Available online 18 September 2023

Keywords:
On-farm WEFE Index
Quadrilateral nexus
Wheat farming

A B S T R A C T

To improve the farming efficiency, Egypt has been struggling to narrow the water, energy, and yield gaps owing to exacerbated water shortage. For quantitative diagnosis of farming performance, the paper presented an on-farm water, energy, food, and carbon-footprint (WEFC) nexus index made up of four equally pillars. The arithmetic average preserved the multi-centric approach and equal importance of the four pillars. The index was applied to test and rank 2,042 wheat-based farmer fields in Egypt representing diverse inputs, agronomic and irrigation practices, soil types, and agroecological conditions. The water metric was the ratio of saved water, difference between maximum water consumption recorded in the country and actual water consumption, to the maximum water consumption. Likewise, the energy metric was obtained. The food metric was the ratio of actual yield to maximum yield in the country. The carbon-footprint metric was the ratio of difference between maximum CO_2 emission in the country and actual emission to the maximum emission. The index values showed a wide range from 18.69% to 87.33% with a high standard deviation emphasizing the diversity of farming practices, soil types, and agroecological conditions. The highest ten values were recorded in fields with sandy soils, relatively large area, drip irrigation, recommended seeding and fertilization rates, well drainage, weeds removal, and tillage. The drip irrigation system in 51 out of 52 fields had above average value. The lowest ten values were in fields with clay soils and flood irrigation, where 18.7% of 1,780 fields exceeded the above average value. Raised beds with furrow irrigation in 83.15% of 184 fields exceeded the above average value. Fertilization rates of nitrogen and phosphorus in 61% and 53% of fields respectively exceeded the recommended rates with no significant reflection on the food metric. The low index values in fields with flood irrigation were attributed to high water losses causing high water consumption, energy consumption, and CO_2 emission. The index was a good indicative of input resources consumption and output production as it varied inversely with water and energy consumption and CO_2 emission and proportionally with yield. Since the high-water consumption was the main entry point for low index values in fields with flood irrigation, changing the irrigation to drip system or revisiting the irrigation scheduling and the estimated applied irrigation water amount were recommended. The index can be utilized to quantify the effectiveness of both recommendations and further new site-specific interventions and to assess their impact at scale. The index also recommended land use consolidation where farmers retain ownership of their lands but with cooperative farming.

1. Introduction

The water, energy, and food (WEF) nexus approach has emerged to manage interlinked resources to enhance water, energy, and food security by increasing efficiency, reducing trade-offs, building synergies, and improving governance, while protecting

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https://doi.org/10.1016/j.wen.2023.09.002
2588-9125/

ecosystems. Despite the increasing recognition of the importance of interlinkages and dependencies between sectors, the nexus approach commonly remains abstract or at the level of political statements. Simpson et al., (2020) presented a national-level composite indicator that has been established for 181 countries for the assessment of applicable water, energy, and food related indicators. The WEF Nexus Index value for Egypt is 52.9, placing the nation in the 121st position among the 181 countries assessed. Egypt has a value of 42.4 for the Water pillar, 60.8 for the Energy pillar, and 55.4 for the Food pillar. The growing WEF demands due to rapidly growing population, the exacerbated water shortage, and the anticipated reduction of Nile flow due to upstream developments are major challenges expected to deteriorate the WEF status of Egypt.

For agriculture, few WEF tools have been developed for enhanced agricultural management and optimal use of inputs on the catchment, subnational, and national levels. Karamian et al., (2021) calculated water and energy consumption, water and energy mass productivity, and water and energy economic productivity for about 300 km^2 cultivated with wheat, maize-grain, and tomato and irrigated by groundwater in the Miandarband plain in Kermanshah province in the west of Iran. Feng et al., (2023) proposed a multiobjective optimization model for the sustainable management of water–energy–land–carbon dioxide systems that optimizes the allocation of water resources and land resources in Sichuan Province, the main grain-producing region in Southwest China. The model provided a new resource utilization plan including allocated area of crop planting and water resources based on assessment of the coordination of resource consumption, economic benefits, and carbon emissions. Taguta et al., (2022) assessed the performance of irrigation technologies in three dominant climate zones (arid, equatorial or tropical, and warm temperate climates) with maize, wheat, and sorghum, from a WEF nexus which considered the metrics of yield, water use efficiency, and energy productivity. This WEF nexus approach applied sustainability polygons to integrate the three metrics into a nexus index representing the holistic performance of the irrigation technologies. Walker et al., (2022) applied a tool for the Inkomati-Usuthu catchment in South Africa for assessment of different practices and interventions and optimize the management and allocation of natural resources.

All available WEF nexus tools on the catchment, subnational, and national levels cannot assess WEF nexus on the farm level holistically since the farm level should contextualize all local priorities under various conditions in the country. In addition, the farm level requires huge data across the country that can holistically enable assessment of all farming systems with different irrigation systems, water resources, energy types, individual crop types, soil types, agroecological conditions, seeding rates, sowing and fertilizer applications, and agronomic practices.

Assessment of WEF nexus on the farm level in Egypt requires understanding the local circumstances. The agriculture sector in Egypt currently suffers from land fragmentation, lack of appropriate good agricultural practices at the field level, dated extension systems, low investment, deteriorating water quality, poor water and fertilizer management, poor involvement of the community, and unreliable and inequitable distribution of water along canals. The agriculture is by far the largest freshwater demanding sector consuming 85% of all current available freshwater resources. Moreover, climate change might have direct impacts on water quantity in Egypt and lead to indirect effects on Mediterranean saltwater intrusion into groundwater. Many scientific publications and reports agree that climate change will have various projections on the Nile River flow, air temperature, precipitation, open water evaporation, evapotranspiration, and Mediterranean saltwater intrusion rate in Egypt. This also influences the groundwater hydraulics and causes greater seawater intrusion in the coastal aquifers in Egypt which in turn leads to the salinity of the soil, deterioration of the quality of crops, loss of productivity, and lack of food (El Demerdash et al., 2022), (Eissa et al., 2017), (Elba et al., 2017). These climate change projections will have direct impacts on water quantity and both land and water salinity in Egypt, which exposes agriculture to vulnerability. It is expected to increase the irrigation water salinity and reduce the crops' water productivity, the total cropped area, and self-sufficiencies of wheat, rice, cereal, and maize, and socioeconomic indicators (Omar et al., 2021).

On the farm level, Egypt struggles to achieve water, energy, and food security. As Egypt relies entirely on irrigated agriculture, water from canals and groundwater should be lifted by pumps as the water level in distributive canals is lower than fields' levels. Future reclamation projects and plans for desalination and wastewater reuse will require additional energy. The water sector in Egypt is currently transforming surface irrigation into pressurized irrigation systems in many old lands in the Nile Valley and Delta for water rationalization. But surface irrigation is the lowest energy consumer among irrigation systems as it takes advantage of the potential energy of water to flood the plots. On the other hand, the transformed pressurized systems consume much more energy dependent predominantly on diesel fuel which subsequently increase the carbon dioxide emissions. Land reclamation for agricultural use is one of the top priorities of the agricultural sector in Egypt, in which the energy is the main determinant of agricultural sustainability. In recent years, the energy sector has been struggling due to highly increased prices and a shortage of diesel supply. Even generating solar energy resource might exposes the water to overconsumption and subsequent shortage as the energy resource is abundant and free of cost. Also, the predominance of overirrigation and diesel pumping, the CO_2 emission is another metric that should be considered. It is very clear that interventions to address the security of one WEF parameter can deteriorate other parameters, and the WEF dimensions have been considered separately.

To achieve the sustainability of agriculture system in Egypt under these challenging local conditions, an integrated resources management approach should replace the existing individual water and energy resources management approaches. By far, there is no WEF nexus tool in Egypt that can assess the farm performance and its specific package of irrigation and agronomic practices, operationalize the nexus approach, and drive transformative actions on the farm level.

There is a great need for Egypt to have an on-farm water, energy, food, and carbon-footprint (WEFC) nexus index presenting a diagnosis for each farm performance combining the four metrics as a quadrilateral nexus rather than assessing each unilaterally. The tool is needed to address pressing issues related to sustainable agricultural water and energy uses and implications on food production and carbon emissions. The tool is needed to identify and upscale the best bundled practices. Hence, the current paper has two objectives as following:

i. To introduce an on-farm WEFC nexus index as a quantitative measure of farm performance and an entry point for the evaluation of the farm status in terms of integrated resource management.
ii. To demonstrate the utilization of the developed on-farm WEFC nexus index in 2,042 wheat-based farmer fields representing diverse inputs, agronomic and irrigation practices, soil types, and agroecological conditions.
iii. To rank the tested fields with description of their bundled irrigation and agronomic practices.

2. Methodology

2.1. WEFC index

The WEFC index was computed as the weighted arithmetic average of the four mail pillars' values: water, energy, food, and carbon-footprint. The average weight preserves the equal weighting and multi-centric approaches of the WEFC nexus pillars which provides equal importance for each. Table 1 presents the four pillars' metrics, each of which was described in sections from 2.1.1. to 2.1.4. The data required for calculation of water, energy, food, and carbon-footprint metrics was collected from a wheat survey in Egypt from 2,042 farmer fields. The survey aimed to identification of existing production practices and understanding the existing yield gaps of wheat in smallholder farming in Egypt. The survey incorporated data on farm and production practices, inputs, tillage types, crop rotation, yield, seeding rate, sowing and fertilizer application, irrigation management, weed, insect, pests, harvesting, use of wheat residue, labor, marketing, income, and price indicators. The survey locations represented the diversity in soil types, agroecological conditions, and all agronomic and irrigation practices in Egypt (Fig. 1).

2.1.1. Water pillar

The value of water pillar metric in each farmer field depended on the amount of saved applied irrigation water in comparison to the maximum applied irrigation water recorded in the country. The maximum applied irrigation water was recorded in many survey fields where flood irrigation without land levelling was applied in old lands in the Nile Valley and Nile Delta. When farmers applied flood irrigation in the survey fields, they released the water from one side of the field and waited until the water reached corners of the other side by gravity. Due to the land systematic irregularity, it was noticed that long time and much water were applied to cover the field entirely. Land depressions were also formed collecting water which was partially lost due to evaporation. Among 2,042 fields of this survey, the maximum amount of applied irrigation water with flood irrigation was 5,647 m^3/ha. In fields where other irrigation methods and agronomic practices reduced the maximum water consumption, the saved water amount was computed as the difference between maximum and actual applied water. The water pillar metric was then calculated as the ratio of saved water to the maximum water.

For example, in another survey field where the drip irrigation withdrew groundwater, the actual applied irrigation water was only 1,788 m^3/ha. The saved water in this field was 3,859 m^3/ha as the difference between the maximum and actual applied water being 5,647 and 1,788 m^3/ha, respectively. In this field, the water pillar metric was 70% as the ration of saved water to the maximum water being 3,859 and 5,647 m^3/ha, respectively. Likewise, the water pillar metrics for the 2,042 fields in the survey were computed as the ratio of saved water to the maximum water.

Table 1
WEFC Index pillars and indicators.

Pillar	Indicator	Pillar Metric Value (%)	WEFE Index (%)
Water	$\frac{SavedWater}{MaximumWater}$	0 – 100	0–––100
Energy	$\frac{SavedEnergy}{MaximumEnergy}$	0 – 100	
Food	$\frac{AgriculturalYield}{MaximumYield}$	0 – 100	
Carbon-footprint	$\frac{Saved\ CO_2\ Emission}{Maximum\ CO_2\ Emission}$	0 – 100	

2.1.2. Energy pillar

The energy pillar metric was the ratio between the saved fuel energy amount to the maximum fuel energy consumed recorded in the country. The total on-farm energy consumption was computed as the sum of both direct and indirect on-farm energy consumption. The direct on-farm energy consumption was all energy consumption inside the farm including irrigation pumping and field operations. Many factors impacted the value of on-farm energy consumption in Egypt. The surface irrigation systems consumed less energy than pressurized irrigation systems. Also, pumping water from a surface canal consumed less energy than pumping groundwater. Diesel fuel was observed to be the main source of energy in agricultural machinery and water pumps in Egypt, and in few cases electrical pumps were used for water withdrawal. All energy consumptions either using diesel or electricity were computed in MJ since the energy equivalent was 56 Megajoules (MJ) for one liter of diesel in average and 3.6 MJ for one kilowatt (KW) of electricity (Yafuz et al. 2014). In addition to direct on-farm energy consumption, indirect energy consumption was consumed due to manufacturing fertilizers and pesticides outside the farm. Fig. 2 shows the energy consumption elements and their values. The highest specific energy for water pumping was with sprinkler irrigation from deep groundwater with a value of 3.9 MJ/m^3 (Yafuz et al. 2014), while the lowest specific energy was with flood and furrow from canal water with a value of 0.1 MJ/m^3 (Farag, 2019). The specific energy for field operations for all irrigation systems was 63 MJ/hour (Canakci et al. 2005). Regarding the indirect energy consumption, the specific energy for nitrogen, phosphate, and potassium fertilizers were 66.14, 12.44, and 11 MJ/Kg, respectively (Rafiee et al. 2010). The seeds specific energy was 3.6 MJ/Kg (Beheshti Tabar et al. 2010). The pesticides specific energy was 275 MJ/Kg (Audsley et al. 2009).

Although the sprinkler irrigation from deep ground water has the highest specific energy, the maximum on-farm energy consumption among all 2,402 farmer fields tested in the current survey was recorded in a field where the flood irrigation was applied. The total consumed energy in this field was 91,173 MJ/ha divided into pumping of 5,647 m3/ha of irrigation water and land operations for a duration of 8 hours as well as for indirect energy consumption to provide 76 and 100 kg/ha of N/P fertilizers respectively to an area of 0.07 ha (1,071 kgN/ha and 1,429 kgP/ha) and 10 kg of seeds (143 kg/ha). This maximum on-farm energy demand for wheat was computed as following:

Energy for water pumping = 5,647 m3/ha * 0.1 MJ/m3 = 564.7 MJ/ha.

Energy for operation = 63 MJ/ha/hour * 8 hours = 504 MJ/ha.

Energy for N Fertilizer = 66.14 MJ/kg * 1,071 Kg/ha = 70,836 MJ/ha.

Energy for P Fertilizer = 12.44 MJ/kg * 1,429 Kg/ha = 17,777 MJ/ha.

Energy for seeds = 3.6 MJ/kg * 143 Kg/ha = 514.3 MJ/ha.

In another survey field, the total energy consumption was 43,845 MJ/ha divided to 12,064 MJ/ha for water pumping by a sprinkler irrigation system withdrawing the water from groundwater, 126 MJ/ha for two hours of land mechanical operation, 31,120 MJ/ha for fertilizers, and 535 MJ/ha for seeds. In comparison to maximum energy consumption in the country, the saved energy in this field was 47,382 MJ/ha. In this field, the energy pillar metric was 52% as the ration of saved water to the maximum water being 47,382 and 91,173 MJ/ha, respectively. Likewise, the energy pillar metrics for the 2,042 fields in the survey were computed as the ratio of saved energy to the maximum energy.

2.1.3. Food pillar

The food pillar metric was the ratio between the actual grain yield from each farmer field to the maximum yield recorded among the 2,402 fields in the country which was 7.49 ton/ha. For

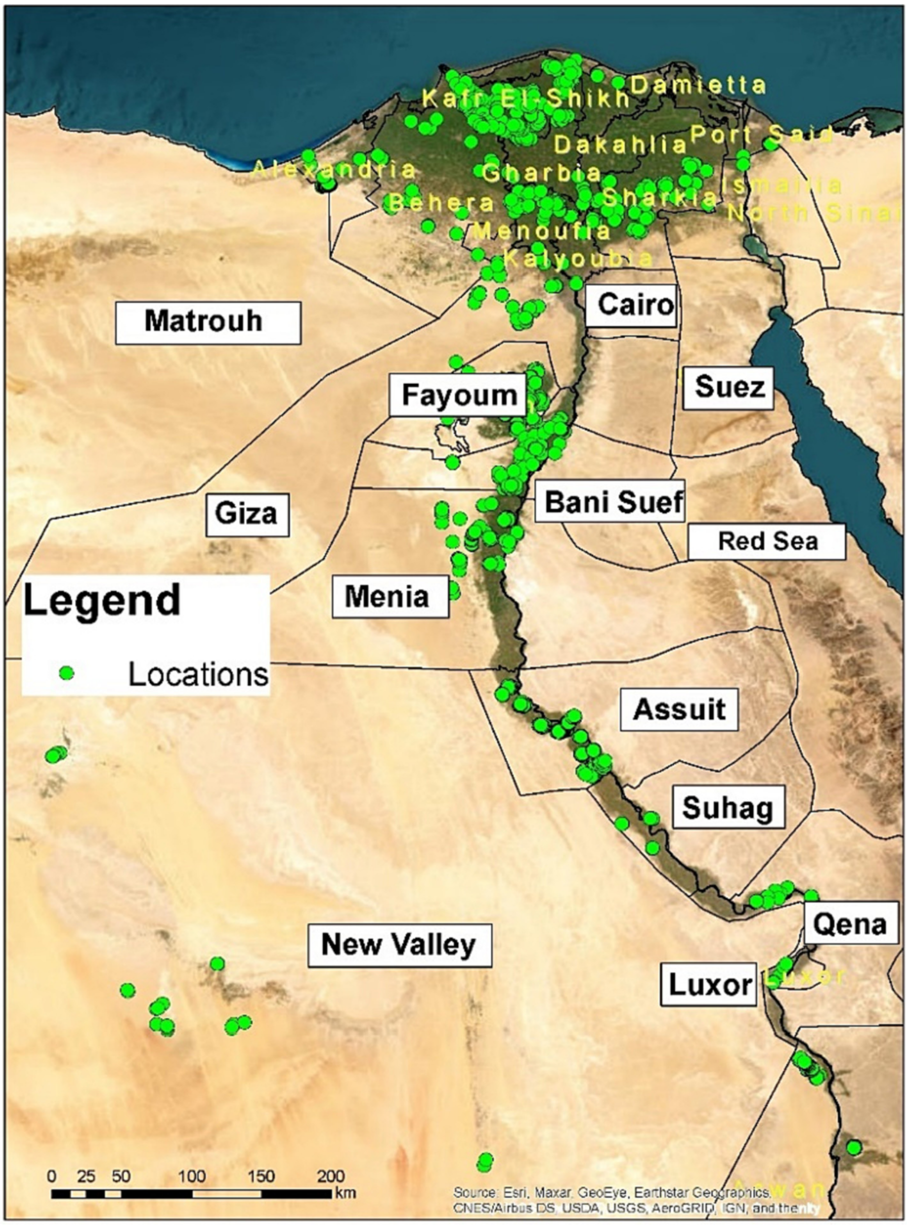

Fig. 1. Locations of 2,042 wheat farmer fields where the WEFC index was demonstrated.

example, a field producing 2.88 ton/ha had a food metric of 38.5% which was a ratio between 2.88 ton/ha to 7.49 ton/ha.

2.1.4. Carbon-footprint pillar

The main source of CO_2 in agriculture in Egypt was the fuel consumption, mainly the diesel consumption. One liter of consumed diesel in the field produced 56 MJ and 2.5 kg of CO_2 (Guatam et al., 2020). Also, one KWh of consumed electricity produced 3.6 MJ and 0.82 kg of CO_2 due to the burning of fossil fuels for electricity generation (Schlömer, 2014). The total amount of CO_2 emission from each field of the current survey was estimated based on the total on-farm energy demand and the total amount of consumed diesel. The carbon-footprint pillar metric was calculated as the ratio between the reduced amount of CO_2 emission to the maximum amount of CO_2 emission recorded in the country. The maximum on-farm energy demand for wheat among the 2,402 fields was 91,173 MJ/ha with diesel water pumping, producing 4,070 kg of CO_2 computed as following:

$$\text{No. of Diesel Liters} = \frac{91,173MJ/ha}{56MJ/L} = 1,628\,\text{L/ha}$$

CO_2 emission = 1,628*2.5 = 4,070 Kg/ha.

If the CO_2 emission in another farmer field was 1,764 Kg/ha, the CO_2 saving was 2,306 MJ/ha, and the indicator value of ecology pillar in this case was 57%. Likewise, the ratios of saved on-farm CO_2 emissions in all 2,402 farmer fields to the maximum energy consumption were obtained as carbon-footprint pillar metrics.

3. Results

The WEFC nexus index was calculated in 2,042 farmer fields in Egypt representing different inputs, tillage types, seeding rates, sowing and fertilizer applications, irrigation systems, soil types, and agroecological conditions. The values of WEFC nexus index in all 2,042 fields were presented in Fig. 3 with an average value of 48.49%, and the highest and lowest values of 87.33% and

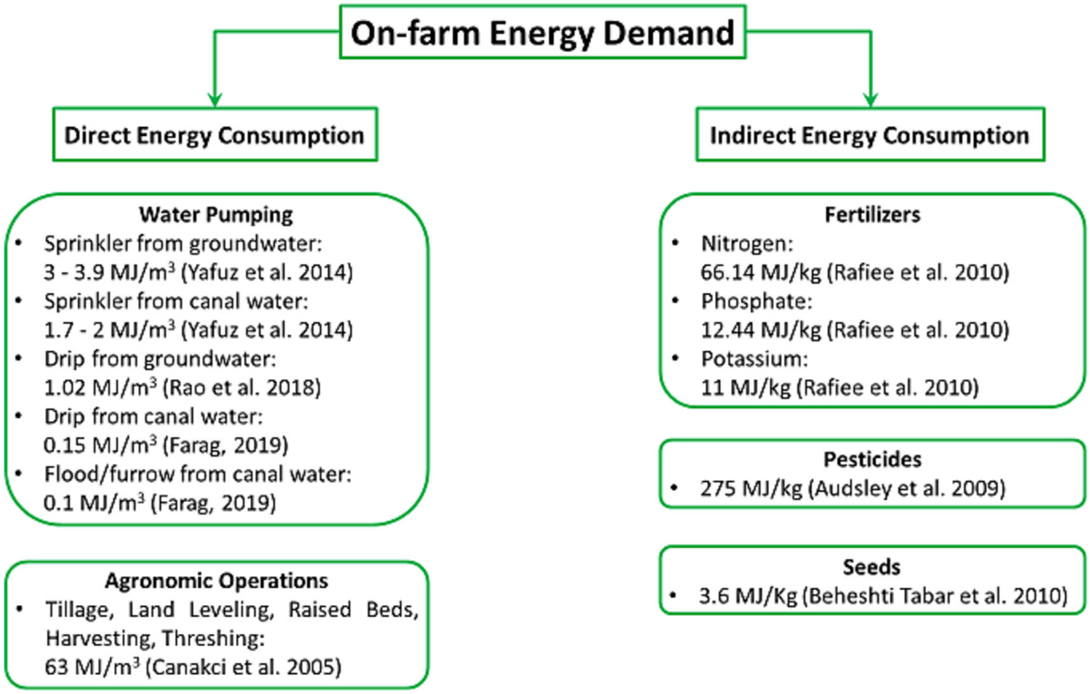

Fig. 2. Energy on-farm consumption elements.

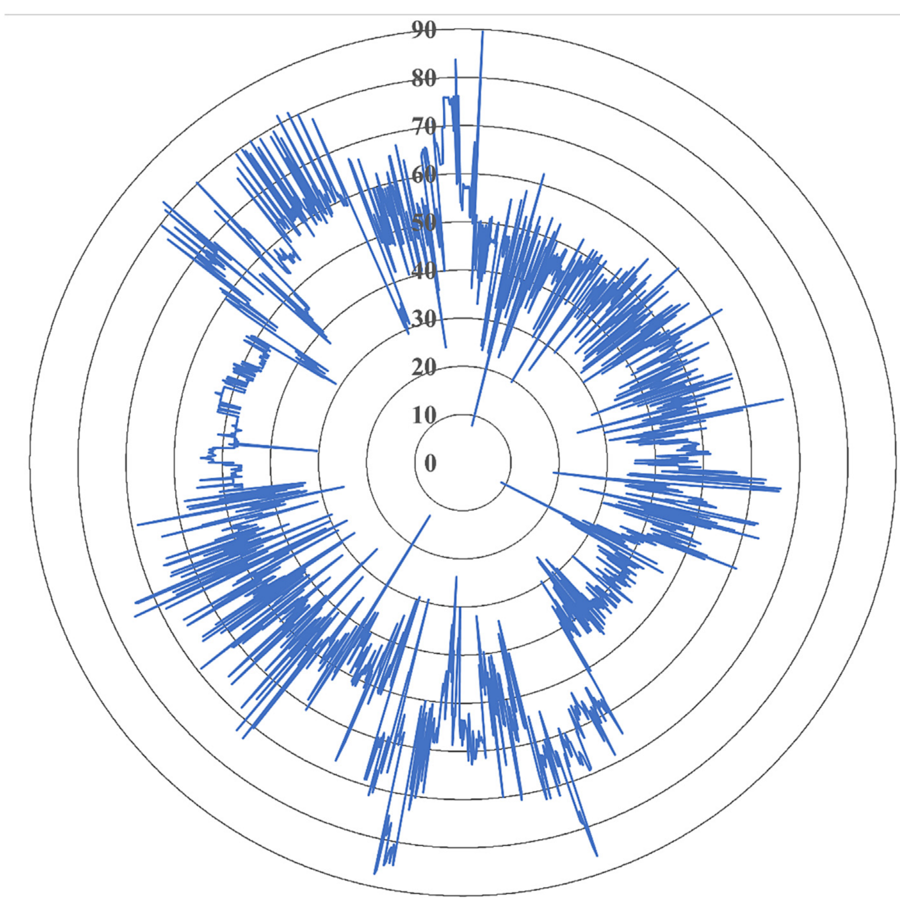

Fig. 3. The values of WEFC nexus index in all 2,042 farmers' fields in Egypt.

18.69%, respectively. Table 2 provided the maximum, average, median, mode, minimum, and standard deviation of water, energy, food, and carbon-footprint metrics for all 2,042 fields involved in this study. The high standard deviation values indicated that the values of water, energy, food, carbon-footprint, and overall index were spread out over a wide range.

The highest and lowest ten ranking farmers' fields for the WEFC nexus index with descriptions of different conditions and practices are shown in Table 3 and Table 4, respectively. The highest ten values were found in new reclaimed lands in El-Menia governorate, where sandy soil was predominant and drip irrigation from deep groundwater was applied. Among the 2,042 farmers' fields investigated in the current study, 52 fields had a drip irrigation system withdrawing the water from deep groundwater, mostly in new reclaimed lands. Out of 52 fields applying drip irrigation, 51 fields had values above the average values. Also, 30 farmers' fields had the sprinkler irrigation system, out of which only 12 fields had values above the average value of all 2,042 farmers' fields with a percentage of 40%. The lowest ten values were found in flat lands with flood irrigation. Among the 2,042 fields of this survey, 1,780 fields were tested in old lands, where flat land with flood irrigation was predominant and characterized by clay soil. Only 333 fields exceeded the above average value of the 2,042 fields with 18.7%. Raised bed land with furrow irrigation was also found in old lands, where 184 fields were tested in this study, out of which 153 fields exceeded the above average value with 83.15%.

N fertilization rates in 61% of fields exceeded the generalized recommended value set by the Ministry of Agriculture and Land reclamation (75 N units/feddan), and P fertilization rates in 53% of fields also exceeded the recommended value (15 P_2O_5 units/feddan). This overfertilization increased the indirect energy consumption and accordingly reduced both the energy and carbon-footprint metrics, but it was not reflected on food pillar metric.

Fig. 4 input quantities of water and energy resources and output quantities of food and CO_2 emission products of three survey fields having the highest, median, and lowest on-farm WEFC nexus indexes in Egypt with descriptions of conditions and practices. WEFC nexus index had an inverse correlation with the input resources since the index value decreased when the input resources increased. The more input resources consumption was, the lower WEFC nexus index value was. WEFC nexus index had a proportional correlation with food output but an inverse correlation with CO_2 emission output. The WEFC nexus index not only enabled quantitative assessment of performance of survey fields regarding nexus, but also showed an indication of input resources consumption and output products quantities.

4. Discussion

There are many factors on the farm level influencing the WEFC nexus status including the irrigation system, water source, planting method, seeding rate and date, fertilization application rate,

Table 2
The statistical data of water, energy, food, and carbon-footprint pillars expressed as index values for all 2,042 farms in Egypt.

Pillar Metric	Min	Max	Average	Mode	Median	Standard Deviation
Water	0	100	3.27	0	0	13.89
Energy	0	100	57.81	56.35	57.42	17.85
Food	7.11	100	77.04	77.80	76.22	13.91
Carbon-footprint	0	100	57.81	56.34	57.43	17.85
WEFC	7.91	87.33	48.93	47.63	47.70	10.67

Table 3
The highest ten ranking farmers' fields with description of agronomic practices.

Field Description	WEFC Index
1.68 ha in Menia governorate with sandy soil, 35 kg dry seeds/ha on dry soil, tillage, 95 kg B-Urea/ha, 60 kg B-SSP/ha, 1,724 m^3/ha by drip irrigation from groundwater with 15 m depth, 100 min machinery for seeding, 60 min machinery for harvesting (Water (W): 70, Energy (EN): 94.41, Food (F): 90.51, Carbon-footprint (C): 94.41)	87.34
1.26 ha in Menia governorate with sandy soil, 50 kg dry seeds/ha on dry soil with tillage, 95 kg B-Urea/ha, 60 kg B-NH_4-NO_3/ha, 1,724 m^3/ha by drip irrigation from groundwater with 15 m depth, 100 min machinery for seeding, 60 min machinery for harvesting (W: 70, EN: 91.78, F: 92.1, C: 91.78)	86.41
1.6 ha in Menia governorate with sandy soil, 45 kg dry seeds/ha on dry soil with tillage, 95 kg B-Urea/ha, 60 kg B-SSP/ha, 1,724 m^3/ha by drip irrigation from groundwater with 20 m depth, 60 min machinery for seeding (W: 70, EN: 91.78, F: 92.1, C: 91.78)	86.37
2.1 ha in Menia governorate with sandy soil, 57 kg dry seeds/ha on dry soil with tillage, 95 kg B-Urea/ha, 60 kg B-NH_4-NO_3/ha, 1,724 m^3/ha by drip irrigation from groundwater with 15 m depth, 100 min machinery for seeding, 60 min machinery for harvesting (W: 70, EN: 91.78, F: 92.1, C: 91.78)	85.26
8.4 ha in Menia governorate with sandy soil, 76 kg dry seeds/ha on dry soil with tillage, 185 kg B-Urea/ha, 60 kg B-NH_4-NO_3/ha, 1,724 m^3/ha by drip irrigation from groundwater with 15 m depth, 100 min machinery for seeding, 60 min machinery for harvesting (W: 70, EN: 87.8, F: 93.68, C: 87.8)	84.90
1.68 ha in Menia governorate with sandy soil, 74 kg dry seeds/ha on dry soil with tillage, 190 kg B-Urea/ha, 1,724 m^3/ha by drip irrigation from groundwater with 15 m depth, 100 min machinery for seeding, 60 min machinery for harvesting (W: 70, EN: 88.1, F: 92.1, C: 88.1)	84.57
2.1 ha in Menia governorate with sandy soil, 60 kg dry seeds/ha on dry soil with tillage, 152 kg B-Urea/ha, 60 kg B-NH_4-NO_3/ha, 1,724 m^3/ha by drip irrigation from groundwater with 10 m depth, 100 min machinery for seeding, 60 min machinery for harvesting (W: 70, EN: 90.92, F: 85.74, C: 90.92)	84.39
1.6 ha in Menia governorate with sandy soil, 57 kg dry seeds/ha on dry soil with tillage, 127 kg B-Urea/ha, 79 kg B-NH_4-NO_3/ha, 1,724 m^3/ha by drip irrigation from groundwater with 15 m depth, 60 min machinery for seeding, 80 min machinery for harvesting (W: 70, EN: 87.1, F: 92.1, C: 87.1)	84.07
2.1 ha in Menia governorate with sandy soil, 57 kg dry seeds/ha on dry soil, tillage, 152 kg B-Urea/ha, 48 kg B-NH_4-NO_3/ha, 1,724 m^3/ha by drip irrigation from groundwater of 15 m depth, 20 hr land preparation machinery, 2.5 hr harvesting machinery, 500 min threshing machinery (W: 70, EN: 87, F: 85.74, C: 87)	82.42
4.2 ha in Menia governorate with sandy soil, 62 kg dry seeds/ha on dry soil, tillage, 152 kg B-Urea/ha, 48 kg B-SSP/ha, 97 kg B-NH_4-NO_3/ha, 1,724 m^3/ha by drip irrigation from groundwater of 15 m depth, 100 min machinery for seeding, 240 min machinery for harvesting (W: 70, EN: 83.2, F: 92.1, C: 83.2)	82.13

Table 4
The lowest ten ranking farmers' fields with description of agronomic practices.

Field Description	WEFC Index
1.26 ha in Fayoum governorate with clay soil, 143 kg/ha of dry seeds on dry soil, 381 kg B-Urea/ha, 476 kg B-SSP/ha, 24 kg B-NH_4-NO_3/ha, 5,764 m^3/ha by flood irrigation from canal water, 690 min machinery for land preparation, and 540 min machinery for threshing (W: 0, EN: 39.44, F: 19.05, C: 39.44)	24.40
0.42 ha in El-Nubaria area in El Behira governorate with calcareous soil, 171 kg/ha of dry seeds on irrigated soil before planting, 362 kg B-Urea/ha, 952 kg B-SSP/ha, 476 kg B-NH_4-NO_3/ha, 5,764 m^3/ha by flood irrigation from canal water, 90 min machinery for land preparation, 90 min machinery for seeding, and 120 machinery for harvesting (W: 0, EN: 0.93, F: 95.27, C: 0.93)	24.20
0.21 ha in Fayoum governorate with clay soil, 143 kg/ha of dry seeds on dry soil, 381 kg B-Urea/ha, 619 kg B-SSP/ha, 238 kg B-NH_4-NO_3/ha, 5,764 m^3/ha by ha by flood irrigation from canal water, 1,170 min machinery for land preparation, and 1,170 min machinery for threshing (W: 0, EN: 23.72, F: 47.63, C: 23.72)	23.82
0.07 ha in Sharkia governorate with clay soil, 143 kg/ha of dry seeds on irrigated soil before planting, 357 kg B-Urea/ha, 714 kg B-SSP/ha, 1,428 kg B-NH_4-NO_3/ha, 5,764 m^3/ha by flood irrigation from canal water, and 60 min machinery for land preparation (W: 0, EN: 6, F: 82.92, C: 6)	23.68
1.2 ha in Sharkia governorate with clay soil, 300 kg/ha of dry seeds on dry soil, 666 kg B-Urea/ha, 170 kg B-SSP/ha, 1,400 kg B-NH_4-NO_3/ha, 5,764 m^3/ha by flood irrigation from canal water, 480 min machinery for land preparation, 180 min machinery for seeding, 360 min machinery for harvesting, and 360 min machinery for threshing (W: 0, EN: 23.47, F: 47.63, C: 23.47)	23.64
0.10 ha in Menofia governorate with clay soil, 180 kg/ha of dry seeds on irrigated soil before planting, 400 kg B-Urea/ha, 500 kg B-SSP/ha, 500 kg B-NH_4-NO_3/ha, 5,764 m^3/ha by flood irrigation from canal water, and 240 min machinery for land preparation (W: 0, EN: 34.12, F: 25.14, C: 34.12)	23.41
1.2 ha in in Salhia area in Sharkia governorate with sandy soil, 13 kg/ha of dry seeds on dry soil, 42 kg B-Urea/ha, 42 kg B-SSP/ha, 42 kg B-NH_4-NO_3/ha, 5,764 m^3/ha by flood irrigation from canal water, 60 min machinery for land preparation, 60 min machinery for seeding, 60 min machinery for harvesting, and 60 min machinery for threshing (W: 0, EN: 34.2, F: 24.13, C: 34.2)	23.13
0.25 ha in Menofia governorate with clay soil, 48 kg/ha of dry seeds on dry soil, 100 kg B-Urea/ha, 200 kg B-SSP/ha, 400 kg B-NH_4-NO_3/ha, 5,764 m^3/ha by flood irrigation from canal water, 120 min machinery for land preparation, 120 min machinery for seeding, 120 min machinery for harvesting, and 120 min machinery for threshing (W: 0, EN: 5.3, F: 74.34, C: 5.3)	21.24
0.42 ha in Sharkia governorate with clay soil, 143 kg/ha of dry seeds on dry soil, 100 kg B-Urea/ha, 238 kg B-SSP/ha, 475 kg B-NH_4-NO_3/ha, 5,764 m^3/ha by flood irrigation from canal water, 60 min machinery for land preparation, 60 min machinery for seeding, 60 min machinery for harvesting, and 60 min machinery for threshing (W: 0, EN: 0, F: 93, C: 0)	19.54
0.08 ha in Menofia governorate with clay soil, 188 kg/ha of dry seeds on irrigated soil before planting, 438 kg B-Urea/ha, 625 kg B-SSP/ha, 1,250 kg B-NH_4-NO_3/ha, 5,764 m^3/ha by flood irrigation from canal water, and 240 min machinery for land preparation (W: 0, EN: 16.73, F: 42.7, C: 16.73)	18.96

energy source, machinery for land preparation and yield harvesting and threshing, and field area. An overall status of on-farm water, energy, food, carbon-footprint nexus in Egypt cannot be presented since a wide range of WEFC nexus index values are obtained in 2,042 fields ranging from 18.69% to 87.33%. The high standard deviation values for water, energy, food, carbon-footprint, and overall index emphasizes the wide range of values for the four pillars and the nexus index. This is due to the diversity of agronomic and irrigation practices, soil types, and agroecological conditions.

The low WEFC nexus index values in farmers' fields with flat lands and the flood irrigation system are attributed to the high-water losses causing high water consumptions since the water is withdrawn from one side of the field and flows by gravity until it reaches corners of the other side of the field. Also, the existing land systematic irregularity and land depressions in the fields collect the water where more water evaporates. Therefore, flat lands with flood irrigation have the maximum water consumption in Egypt, and accordingly, the water metric severely declines. Due to this high-water consumption in flat lands with flood irrigation, their energy consumption exceeds the energy consumption in fields with drip and sprinkler irrigation although their specific energy for water pumping per water volume unit is much less. Since the carbon-footprint pillar is directly correlated to the energy pillar, flat lands with the flood irrigation system also have low carbon-footprint metrics.

The raised bed lands with the furrow irrigation system achieve relatively higher WEFE nexus index values than flat lands with the flood irrigation system. The main rationale for that is the lower water losses caused by better distribution of water across the fields. Lower water consumption than in flat lands with flood irrigation raises the values of water metric. Since water consumption is less, the energy consumption is less in raised bed lands with the furrow irrigation system than in flat lands with flood irrigation even in fields consuming extra energy for machinery of raised beds preparation. Hence, the energy metric in raised bed lands with the furrow irrigation system is higher than in flat lands with flood irrigation reflecting on higher low carbon-footprint metrics.

In general, the rankings of water and energy consumption and CO_2 emission from the highest to lowest in all 2,042 fields start with flat lands of flood irrigation, then raised beds with furrow irrigation, then fields of sprinkler irrigation, and ends with fields of drip irrigation. However, values of food pillar are similar for most of the 2,042 tested fields of well drained, free of weeds, and served tillage, regardless of the applied irrigation systems.

The highest ten ranking fields among all 2,042 fields have relatively large areas and undertake integrated resources management by applying the drip irrigation system consuming less water and energy, seeds and fertilization rates recommended by extension system, well drainage, weeds removal, and tillage. This finding backstops the land use consolidation of fragmented lands where farmers retain ownership of their lands but with cooperative farming. This agrees with Giller et al., (2021) who figured out that increasing farm sizes in North-West Europe resulted in massive overproduction and a reduction of negative impacts on the environment. Understanding the land use and change is important to manage the WEF nexus resources efficiently. This agrees with Wolde et al., (2021) proving that land use and change can resolve the current dilemmas between land, water, energy, and food sector policies, improve resource productivity, lower environmental pressure, and enhance human wellbeing and security. In addition to land use consolidation, the drip irrigation system also achieves a better status of water, energy, food, and ecology than other irrigation systems. This agrees with Khalifa et al., (2020) and Deshmukh, (2015) who have shown that water saving, electricity saving, irri-

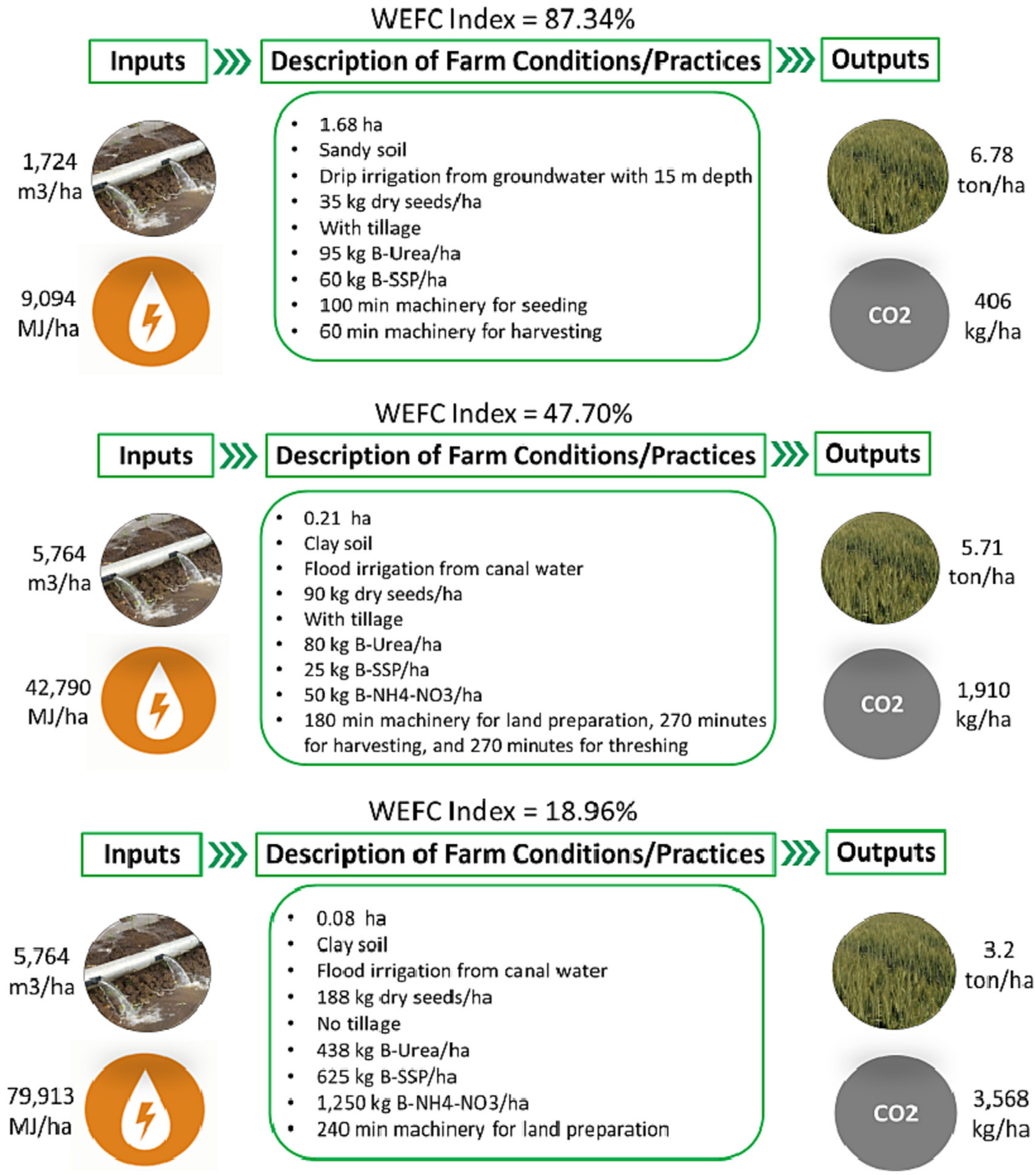

Fig. 4. Input resources and output products of the highest (up), median (middle), and lowest (bottom) on-farm WEFC nexus values in Egypt with descriptions of conditions and practices of fields.

gation efficiencies and yield of crops using drip irrigation are substantially higher than crops irrigated by the conventional flood irrigation methods. Taguta et al., (2022) also confirmed this fact who found that the irrigation modernization pathway to drip technology from either furrow or sprinkler systems improves irrigated agriculture's WEF nexus performance for more crop per drop per joule per hectare under climate change.

The WEFC nexus index values are indicative of input resources consumptions and output products quantities. The index value has an inverse correlation with the water and energy consumptions as input resources. The index value has a proportional correlation with food output but an inverse correlation with CO_2 emission output.

To achieve high on-farm WEFC nexus index values in Egypt, no generalized package can be recommended to the entire country due to the discrepancy in agroecological conditions and soil characteristics. The index can quantitatively assess the nexus performance of site-specific packages of practices under certain conditions and quantify the impact of new interventions on the nexus status. The index this way can be used to maximize the nexus on the farm level under various agroecological conditions and soil types. It is recommended to further investigate the potential of drip irrigation in old lands with heavy clay soils. It is also recommended to revisit estimation of the applied irrigation water to flat lands with flood irrigation, because the high-water consumption in these fields is the main entry point of having very low WEFC nexus index values.

5. Conclusion

The current paper narratively assesses the status of water, energy, food, and carbon-footprint individually on the farm level in 2,042 fields representing the diversity of wheat agronomic practices, irrigation management practices, agroecological conditions, and soil types in Egypt. The paper also examines the interrelationships between on-farm WEFC sectors under all diverse conditions in the entire country. The developed WEFC nexus index measures the extent of managing the resources in an integrated manner. The wide range of index values and its pillar metrics with high standard deviations reflects the wide diversity of agronomic and irrigation practices, soil types, and agroecological conditions in the country. The WEFC nexus index is a good indicative of input resources consumption including water and energy and output production including yield and CO_2. The index varies inversely with water consumption, energy consumption, and CO_2 emission and proportionally with the yield. The highest water and energy consumptions and CO_2 emission are in flat lands of flood irrigation, then raised beds with furrow irrigation, then fields of sprinkler irrigation, and fields of drip irrigation. But yields are almost equal for most of tested fields of well drained, free of weeds, and served tillage, regardless of the applied irrigation systems. The highest-ranking fields are relatively large in new reclaimed lands with sandy soils and an integrated package of resources in which drip irrigation system, recommended seeds and fertilizers rates, well drainage, weeds removal, and tillage are applied. The lowest-ranking fields are in old lands with clay soils, flood irrigation system without land leveling and with overfertilization. Recommended package of practices achieving high index values can be introduced to decision makers, but no generalized package can be recommended to the entire country due to the discrepancy in agroecological conditions and soil characteristics. The index considers site-specific practices under certain conditions. The index can quantify the effectiveness of new interventions and maximize the nexus on the farm level under various agroecological conditions and soil types and assess their impact at scale. Two recommendations are introduced to flat lands with flood irrigation since their high-water consumption is the main entry point of having very low WEFC nexus index values. First, it is recommended to prove the concept of transforming flood irrigation to drip irrigation in old lands with heavy clay soils. Parallelly, it is also recommended to revisit estimation of the applied irrigation water. Valuation of both recommended interventions by the current WEFC will help identify the more effective one. WEFC index assessment recommends the land use consolidation approach under Egyptian conditions where farmers retain ownership of their lands but with cooperative farming.

The submitting author is responsible for ensuring that the contributions of all authors are correct. It is expected that all authors will have reviewed, discussed, and agreed to their individual contributions as shared by the submitting author. The authors' contribution statement will be published with the final article and should accurately reflect contributions to the work.

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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