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Assessing greenhouse gasses emitted from on-farm irrigation pumps: Case studies from Egypt

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Abstract Increasing greenhouse gas emission has become a worldwide concern as it is considered a major driver of global warming and climate change. Clear picture of greenhouse gasses emissions due to utilizing energy for on-farm irrigation pumps is a key guide for decision makers to identify strategies for greenhouse gasses emission reduction that consequently impact on the national and international level. The current study determined the carbon emitted from three common categories of diesel and electric on-farm irrigation pumps in Egypt. A set of environmental, economic, and social evaluating indicators were applied to carry out a comparative analysis among the pump categories in three study areas at El-Behera Governorate. The study showed that pumping 1 m^3 of water for irrigating the cropping pattern at the study areas produces an average of 690 ton CO_2. The study illustrated that electrical pumps are more environmentally, economically, and socially advantageous than diesel pumps.

1. Introduction

Greenhouse gas emissions depend on global population, economic, technological, and social trends [1–3]. In its effort to control greenhouse emission, the United Nation Framework Convention on Climate Change (UNFCCC) imposed obligations on developed countries to reduce their emissions through Kyoto protocol, in addition to contributing the rest of countries in the activities to combat climate change [4,5].

The United Nations Climate Change Conferences are yearly held in the framework of UNFCCC. They serve as the formal meeting of the UNFCCC Parties (Conferences of the Parties (COP)) to assess progress in dealing with climate change. Since COP1 in Berlin at the end of 1995, Egypt is sharing in all COP meetings.

Egypt signed the Kyoto protocol in 15/03/1999, ratified in 12/01/2005 and put into force in 12/04/2005. As a non-annex I country, Egypt is one of the countries expecting to face damaging effects due to climate change, although its contribution to the global greenhouse gas (GHG) emissions is negligible compared to developed countries [6]. However, mitigation measures contained in national plans and governmental studies are in progress. The objective of mitigation measures

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Nomenclature

a_i	cultivated area of crop *i*
A_e	exhaust flow rate of the engine
BCM	Billion Cubic Meter
CFE	carbon dioxide emission factor of producing energy from Power Plant
CFE_D	default CO_2 emission factor of fuel
CMLWE	Centralized Management of Land, Water, and the Environment
CO_2	carbon dioxide
CO_{2d}	CO_2 emission from diesel irrigation pumps
CO_{2E}	CO_2 emissions due to consuming fuel for producing electricity at El Mahmoudia Power Plant
CO_{2e}	carbon emission from the pump
Co_{2hi}	carbon emission per ha
CO_{2m}	concentration of CO_2 in the exhaust
CO_{2w}	carbon emission per unit volume of water
CO_{2CP}	carbon emission of current cropping pattern at the study areas
COP	Conferences of the Parties
F	Fuel consumption
GHG	Greenhouse gas
$GgCO_2$	gigagram of carbon dioxide
ha	hectare
hp	hours power
IIIMP	Integrated Irrigation Improvement and Management Projects
IIP	Irrigation and Improvement Projects
IIS	Irrigation Improvement Sectors
$KgCO_2$	kilograms of carbon dioxide
kW h	kilowatt-hour
L/s	litter per second
m^3/s	cubic meter per second
mg/L	milligram per litter
MWRI	Ministry of Water Resources and Irrigation
O&M	operation and maintenance
p	Energy consumed by the pumps' engine
P_T	total power generation from El Mahmoudia Power Plant
Q	discharge of the pump
tCO_2	ton of carbon dioxide
TJ	Terajoule
UNFCCC	the United Nation Framework Convention on Climate Change
w_i	water requirement per ha of crop *i* at the study areas

is to create a national greenhouse gas mitigation portfolio to support the process of sustainable development in Egypt [7,8].

Water management in Egypt faces numerous challenges including population increase, water scarcity, and deterioration of water quality. Additionally, these challenges include the need for adapting to climate change and reducing emissions of greenhouse gasses. In Egypt, the total GHG emission was about 318 Million tons eq. CO_2 in 2010 [9]. In irrigated agricultural areas, there are different sources for GHG emissions. These sources include enteric fermentation, manure management, rice cultivation, synthetic fertilizers, manure applied to soils, manure left on pasture, crop residues, cultivation of organic soils, burning – crop residues, burning savanna, and energy use, Fig. 1. In irrigated agricultural areas, one of the main causes of greenhouse gasses emissions is the use of energy for operating irrigation pumps. Energy use in irrigated agriculture includes field operations and tillage, seed sources, chemicals, fertilizer, harvest, and irrigation. Pumping activities in irrigation sector in Egypt take up a significant share of energy consumption.

In spite of rehabilitation of some irrigation and drainage pump stations in Egypt, they need to be monitored and evaluated regularly. Furthermore, the energy efficiency of some stations is still need to be improved. Reduction of GHG in the irrigated agriculture is one of elements that affect the improvement of mitigation and adaptation opportunities to climate change. GHG emissions associated with irrigation water management are partially been considered in water management and planning. Few studies consider the trade-offs between irrigation water and GHG emissions of the water sector.

The main goal of the current research is highlighting the importance of appending greenhouse gasses mitigation of irrigation pumps in the national strategies. The study gives a clear picture of the carbon emission due to utilizing energy for on-farm irrigation pumps in three areas at El-Behera Governorate in Egypt. This picture could be used as a key guide to identification of options for emission reduction that consequently impacts on the national level. Through the research, the carbon dioxide (CO_2) emitted due to irrigation activities was measured in the three studied areas. CO_2 emissions per unit volume of irrigation water and unit of irrigated cultivated area were analyzed. In addition, the cost of operation and maintenance, the cost of energy, and the acceptance of the farmers for different categories of pumps were determined. CO_2 emissions due to the current cropping pattern in the studied areas were appraised.

2. Irrigation system in Egypt

The Egyptian irrigation system is considered one of the most complicated systems in the world. Water in the River Nile is diverted to agricultural lands through main canals, branch canals and sub-branch canals. The branch canals deliver water into smaller tertiary channels (mesqas) and water is conveyed from the mesqas, or in some cases directly from canals, to the fields by farm ditches or "marwas".

In some regions, field pumps are used on-farm level to lift water from canals to mesqas for irrigation purpose. Mesqas feed marwas which are temporarily constructed for a single cropping season only. According to data collected from [10], the area served by irrigation pumps in year 2010 represents about 75% of the total cultivated area, as shown in Table 1. The amount of water pumped for irrigating this area is about 33.5 Billion Cubic Meter (BCM) based on the average year water consumption per hectare (ha) which is about 11,900 m^3.

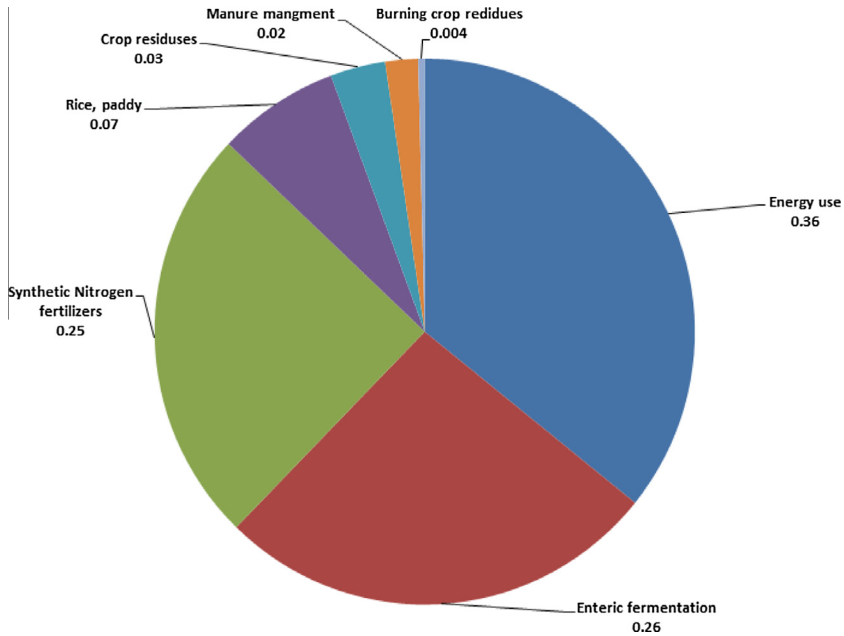

Figure 1 CO_2 emissions due to utilizing energy in agriculture – Egypt [11].

3. GHG in irrigated agricultural areas in Egypt

In Egypt, the main sources of GHG are enteric fermentation, manure management, rice cultivation, synthetic fertilizers, manure applied to soils, crop residues, burning crop residues, and energy use. Energy use results in producing 36% of GHG in the irrigated areas, as shown in Fig. 1. In 2010 GHG emitted due to using energy in agricultural is about 11,966 ($GgCO_2$ equ) [11]. 27% of this amount is emitted due to energy use for irrigation. Carbon dioxide represents 90% of the GHG emitted due to energy use for irrigation.

4. Methodology

A comparative analysis among three categories of on-farm irrigation pumps in Egypt is carried out. This comparative analysis was achieved by carrying out the following steps, as shown in Fig. 2: (i) selecting the study areas, (ii) conducting field missions to do the following: collect data and information required for the study, direct measuring of CO_2 concentration from irrigation pumps at the study areas, and performing a sampled survey, (iii) calculating and analyzing environmental, economic, and social indicators. The environmental indicators include CO_2 emitted from diesel pumps, CO_2 emitted due to utilizing electrical pumps, CO_2 emission per unit volume of irrigation water, and CO_2 emission per unit of cultivated area. The economic indicators comprise the cost of operation and maintenance of the pumps and the cost of energy for operating the pump. The social indicator embraces the satisfaction of farmers with the pumps' type, (iv) estimating CO_2 emission of the current cropping pattern at the study areas, and (v) analyzing the results.

Table 1 The cultivated area distributed base on the type of irrigation.

Irrigation system	Lower Egypt	Upper Egypt	Desert	Total
	Served area (ha)			
Pumping	1,887,483	906,010	22,050	2,815,544
Flood	43,604	247,568	45,257	336,429
Manual lifting	419	915	–	1,335
Sprinkler	131,482	21,504	20,217	173,203
Drip irrigation	263,184	91,026	32,312	386,523
Total	2,326,172	1,267,023	119,836	3,713,033

Source: [10].

4.1. Selecting the study areas

On-farm irrigation pumps at three branch canals at El-Mahmoudia canal (main canal) at El-Behera Governorate in Egypt were selected to be studied; Table 2 illustrates the characteristics of the selected pumps. The selection of three studies areas was based on consultation meeting with specialist and engineers of the Irrigation Improvement Sectors (IIS) of Ministry of Water Resources and Irrigation (MWRI) at Cairo and El-Behera Governorates. The description of the pumps on the three canals is as follows, Fig. 3:

(i) Sixteen diesel irrigation pumps out of 27 were selected at El-Nakhla branch canal, as examples of diesel pumps at improved canal, and these pumps have been rehabilitated/installed through the Irrigation and Improvement Projects (IIP) at MWRI. El-Nakhla canal is allocated on the right side of El-Mahmoudia canal at 27.7 km from the intake. The canal length is 2.6 km and its total served area is 572 ha.
(ii) Ten diesel irrigation pumps were selected at Hamed Minisy branch canal, as examples of diesel pumps at non-improved canal. Only ten sample pumps were selected due to the difficulty of carrying out the

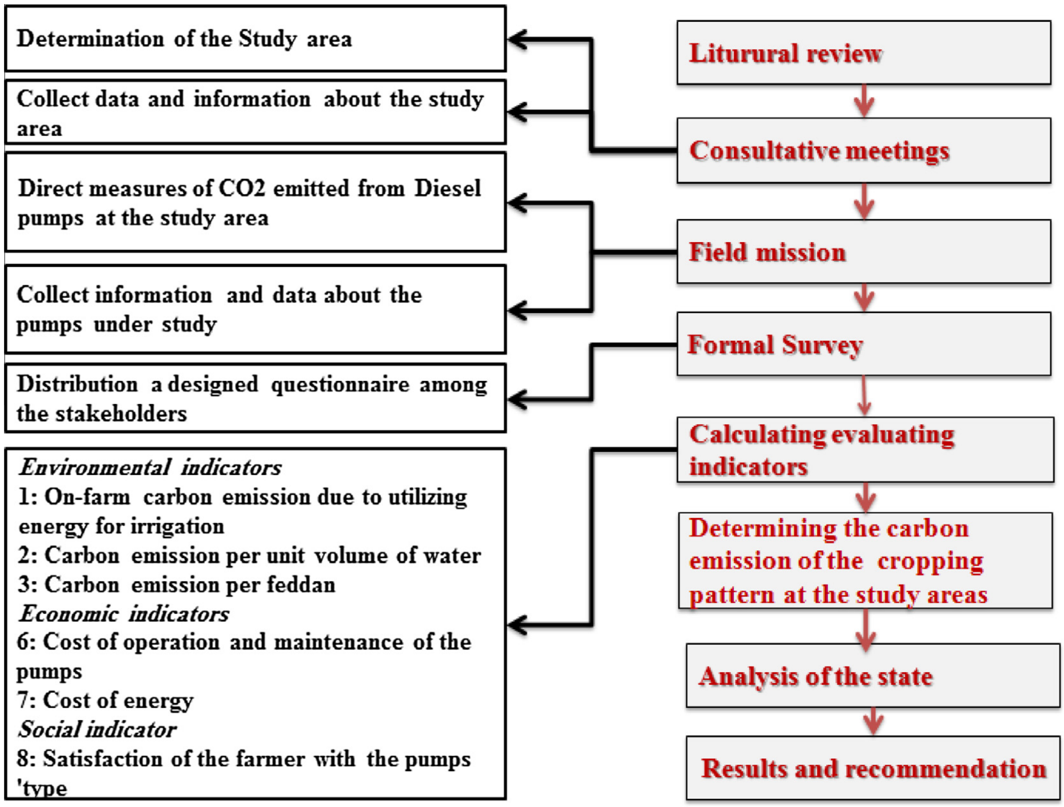

Figure 2 Methodology framework.

Table 2 The characteristics of the selected on-farm irrigation pumps at the study areas.

El-Nakhla canal[a] Diesel pumps at improved canal			Hamed Minisy canal[b] Diesel pumps at non-improved canal			Nekla canal[a] Electrical pumps at improved canal			
Sample abbr.	Q (l/s)	H (m)	Sample abbr.	Q (l/s)	H (m)	Sample abbr.	Q (l/s)	H (m)	Number of pumps
S1 (Na)	60	9.19	S1 (M)	20	2	S1 (Ne)	20	13	39
S2 (Na)	60	9.13	S2 (M)	20	2	S2 (Ne)	30	10.5	7
S3 (Na)	60	9.57	S3 (M)	20	2	S3 (Ne)	30	15	4
S4 (Na)	60	9.49	S4 (M)	20	2	S4 (Ne)	30	8	2
S5 (Na)	60	9.29	S5 (M)	20	2				
S6 (Na)	60	9.66	S6 (M)	20	2				
S7 (Na)	60	9.57	S7 (M)	20	2				
S8 (Na)	60	9.18	S8 (M)	20	2				
S9 (Na)	60	9.36	S9 (M)	20	2				
S10 (Na)	60	9.29	S10 (M)	20	2				
S11 (Na)	60	9.17							
S12 (Na)	60	9.99							
S13 (Na)	60	9.19							
S14 (Na)	60	13.93							
S15 (Na)	60	10.13							
S16 (Na)	60	9.86							

[a] *Source:* Irrigation Improvement Sectors at El-Behera Governorate.
[b] *Source:* Collected information through the field survey.

required measuring (as the pumps on Hamed Minisy canal are owned by farmers and some of them did not exist in the field during the missions). However, according to collated information during the field missions, all the pumps at the study area on Hamed Minisy canal have the same characteristic of the sample pumps. Hamed Minisy canal is allocated on the right side of El-Mahmoudia canal at 7.6 km from the intake. The canal length is 14.9 km and its total served area is 3137 ha.

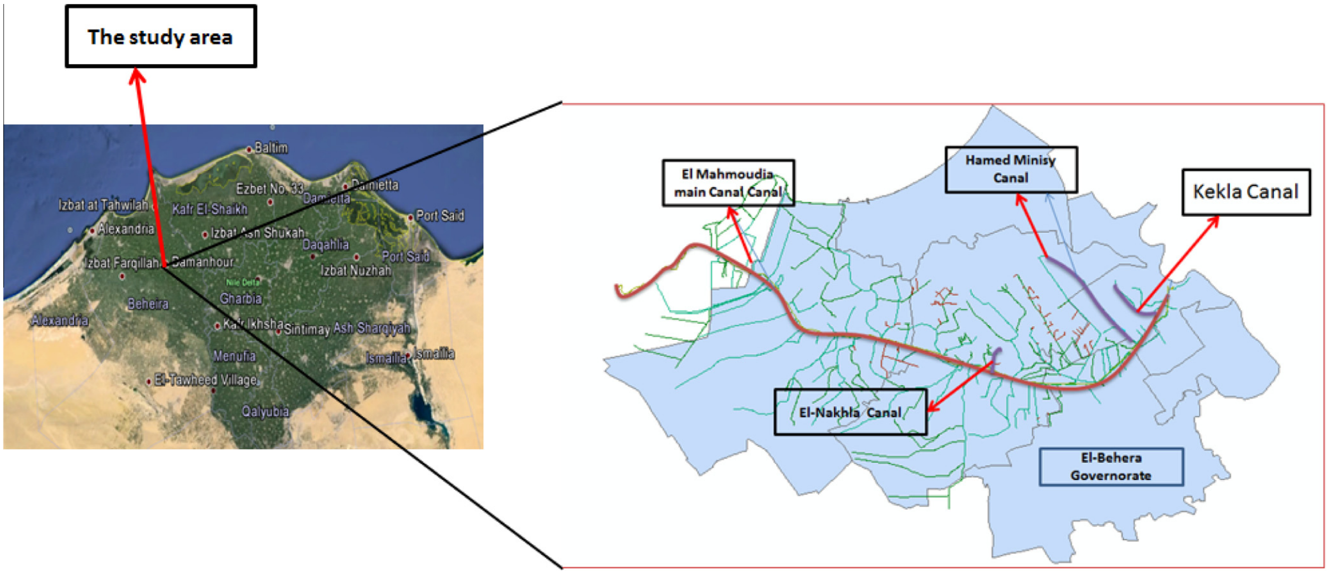

Figure 3 The study areas.

(iii) Fifty two electrical irrigation pumps at Nekla canal, branch canal, as examples of electrical pumps at improved canal through these pumps have been rehabilitated/installed by the Integrated Irrigation Improvement and Management Projects (IIIMP) at the MWRI were selected. Nekla canal is allocated on the right side of El-Mahmoudia canal at 2.02 km from the intake. The canal length is 8.4 km and its total served area is 1453 ha.

4.2. Conducting field missions

Field missions were conducted to do the following:

(i) Collect data and information, which included pumps' location, horsepower, discharge, head, and served area and cropping pattern.
(ii) Direct measuring of CO_2 emitted from diesel on-farm irrigation pumps at the study areas (16 pumps at El-Nakhla and 10 at Hamed Minisy canals). The CO_2 concentration in the exhaust of each pump under study was measured using "Aeroqual-series-500" instrument that enables accurate real-time surveying of air pollutants, all in an ultra-portable handheld monitor. The instrument is used for short term air quality studies and carrying out checks on pollution hot spots.

4.3. Determine evaluating environmental, economic, and social indicators

4.3.1. Environmental indicators

The environmental indicators were selected to represent the on-farm carbon emissions due to utilizing energy for irrigation. The environmental indicators include the following: CO_2 emitted from utilizing diesel and electrical pumps, CO_2 emission per unit volume of water and per unit of cultivated area, and CO_2 emission due to the current cropping pattern of the three study areas. These indicators were determined and calculated as follows:

4.3.1.1. Carbon dioxide emission due to utilizing diesel pumps. Carbon dioxide emission from diesel irrigation pumps (CO_{2d}, mg/s) is calculated applying Eq. (1):

$$CO_{2d} = CO_{2m} \times A_e \tag{1}$$

where CO_{2m} (mg/L) is CO_2 concentration in the pump's exhaust (the CO_2 concentration in the pump's exhaust was measured for at least 15 min and then the readings were averaged) and A_e (L/s) is the exhaust flow rate of the engine. According to the engine model and horsepower, the exhaust flow rate of the engines was determined from Donaldson engine horsepower and exhaust guide [12]. The engine model and horsepower were determined during the field survey and from IIS at El-Behera Governorates.

4.3.1.2. Carbon dioxide emission due to utilizing electric pumps. El Mahmoudia Power Plant submitted electricity to the pumps at Nekla canal. The source of fuel for El Mahmoudia Power Plant is mixed of Natural Gas (N.G.) and Light Fuel Oil (L.F.O) [13]. CO_2 emissions due to consuming fuel for producing electricity at El Mahmoudia Power Plant (CO_{2E}, $KgCO_2$) were estimated applying Eq. (2).

$$CO_{2E} = P \times CEF \tag{2}$$

where p (kW h; 1 kW h = 0.746 hp) is the energy consumed by the pumps' engine. CFE ($KgCO_2$/kW h) is the carbon dioxide emission factor of producing energy from the Power Plants. CFE is calculated by applying Eq. (3).

$$CFE = \frac{CFE_D \times F}{P_T} \tag{3}$$

where CFE_D ($KgCO_2$/TJ) is the default CO_2 emission factor of fuel; CFE_D is identified from [2], F (TJ) is fuel consumption, P_T (kW h) is total power generation from El Mahmoudia

Power Plant. Data of F and P_T were collected from [13] for year 2013.

4.3.1.3. Carbon emission per unit volume of water. Carbon emission per unit volume of water (CO_{2w}, $KgCO_2/m^3$) is estimated applying Eq. (4).

$$CO_{2w} = \frac{CO_{2e}}{Q} \quad (4)$$

where CO_{2e} ($KgCO_2/s$) is the carbon emission from the pump and Q (m^3/s) is the discharge of the pump.

4.3.1.4. Carbon emission per unit of cultivated area. Carbon emission per ha (CO_{2hi}, $KgCO_2/ha$) of the main crops was estimated applying Eq. (5).

$$CO_{2hi} = CO_{2w} \times w_i \quad (5)$$

where w_i (m^3/ha) is the water requirement per ha for crop i at the study areas. w_i is collected from Water Management Research Institute (WMRI) [14].

4.3.1.5. Carbon emission of the cropping pattern at the study areas. Carbon emission of current cropping pattern of the canals at the study (CO_{2CP}, $KgCO_2$) is estimated applying Eq. (6).

$$CO_{2CP} = \sum_{i=1}^{i=n} CO_{2hi} \times a_i \quad (6)$$

where a_i (ha) is the cultivated area of crop i and n is the total number of cultivated crops in the study area.

4.3.2. Social and economic indicators

A questionnaire was prepared to complete the collection of data and information needed to carry out a social and economic comparison among the different types of pumps. The questionnaire included the following: (i) The pumps' location (*e.g.* the name of Governorate, district, village, irrigation district, and the canal on which the pump is located), (ii) the farm size, (iii) information about the farmer (*e.g.* name, gender, age and education), (iv) the energy and operation and maintenance costs of each pump, and (v) the farmers' opinion about the performance of diesel and electrical pumps and the problems and constraints they face. The selected interviewed farmers' samples for the study were the operators of the pumps at the study areas. The total number of interviews was 40 farmers (16, 10 and 14 at El-Nakhla, Hamed Minisy, and Nekla branch canals and their mesques respectively).

5. Results and discussions

5.1. Carbon emission due to irrigation at the study areas

5.1.1. Carbon dioxide emission due to utilizing diesel pumps at El-Nakhla canal

Carbon dioxide concentrations in the exhaust of the sixteen improved diesel pumps at El-Nakhla canal were directly measured as described in Section 4.2. The pumps heads range from 9 to 13 m, the discharge of the pumps is 0.06 m^3/s, and the horsepower of the pumps ranges between 9.9 and 9.2 hp. Before operating the pumps, the average CO_2 concentration was 428 ppm in the air. The measured CO_2 concentration in exhaust of the sixteen pumps ranges between 664 and 2765 ppm, as shown in Fig. 4a. The average CO_2 concentration is 1495 ppm.

The estimated CO_2 emissions per unit volume of water that was pumped by the sixteen improved pumps at El-Nakhla canal range from 0.37 to 1.40 $KgCO_2/m^3$, as shown in Fig. 5a. The average of CO_2 emissions per cubic meter of pumped water is 0.87 $KgCO_2/m^3$. The average CO_2 emissions per ha of wheat, maize, rice, long clover, broad bean, sugar beet, vegetables, cotton, and sugar beet are about 3.43, 5.79, 12.66, 5.73, 2.67, 5.92, 6.57, and 4.82 tCO_2/ha respectively, as shown in Table 3. The average CO_2 emissions per ha served by the pumps at El-Nakhla canal are 5.95 tCO_2/ha.

5.1.2. Carbon dioxide emission due to utilizing diesel pumps at Hamed Minisy canal

Carbon dioxide concentrations in the exhaust of ten non-improved diesel pumps at Hamed Minisy canal were measured. During the field survey, the type of the mobile pumps own by farmers that were found in the study area has the following characteristics: the pumps' heads are 2 m, their discharges are 0.02 m^3/s and their horsepower are 7 hp. Before operating the pumps the average CO_2 concentration was 437 ppm. The measured CO_2 concentration in the exhaust of the ten pumps ranges between 654 and 1380 ppm, as shown in Fig. 4b. The average of CO_2 concentration in the exhaust of the ten pumps is 895 ppm.

The calculated CO_2 emissions per unit volume of pumped water by the ten non-improved pumps at Hamed Minisy canal range from 0.85 to 1.80 $KgCO_2/m^3$, as shown in Fig. 5b. The average of CO_2 emissions per cubic meter of pumped water is 1.11 $KgCO_2/m^3$. The average carbon dioxide emissions per ha of wheat, maize, rice, long clover, broad bean, vegetables, cotton, and sugar beet cultivated in the command area of Hamed Minisy canal are about 4.13, 6.97, 15.23, 6.90, 3.21, 7.12, 7.90, and 5.80 tCO_2/ha respectively, as shown in Table 3. The average CO_2 emissions per ha of area served by the pumps at Hamed Minisy canal are 7.16 tCO_2/ha.

5.1.3. Carbon dioxide emission due to utilizing electric pumps at Nekla canal

The discharge of the pumps ranges is 0.02, 0.03 and 0.04 m^3/s at Nekla canal and the pumps heads range from 10.5 to 15 m. The use of electrical pumps reduces the carbon dioxide emission in the study area. However, it increases the CO_2 emission at the national scale.

The calculated CO_2 emissions per unit volume of pumped water, as shown in Fig. 5c, for 39, 7, 4, 2 improved electrical pumps at Nekla canal are about 0.01, 0.02, 0.03, and 0.02 $KgCO_2/m^3$ respectively, as shown in Fig. 5c. The estimated CO_2 emissions from the pumps at Nekla canal are due to fuel consumption at El Mahmoudia Power Plant that submitted electricity to these pumps. The average of CO_2 emissions per cubic meter of pumped water by the 52 pumps is 0.02 $kgCO_2/m^3$. The average CO_2 emissions per ha, for the 52 pumps, of wheat, maize, rice, long clover, broad bean, vegetables, cotton, and sugar beet cultivated in the command area Nekla canal are about 0.10, 0.17, 0.37, 0.17, 0.08, 0.17, 0.19, and 0.14 tCO_2/ha respectively, as shown in Table 3. The

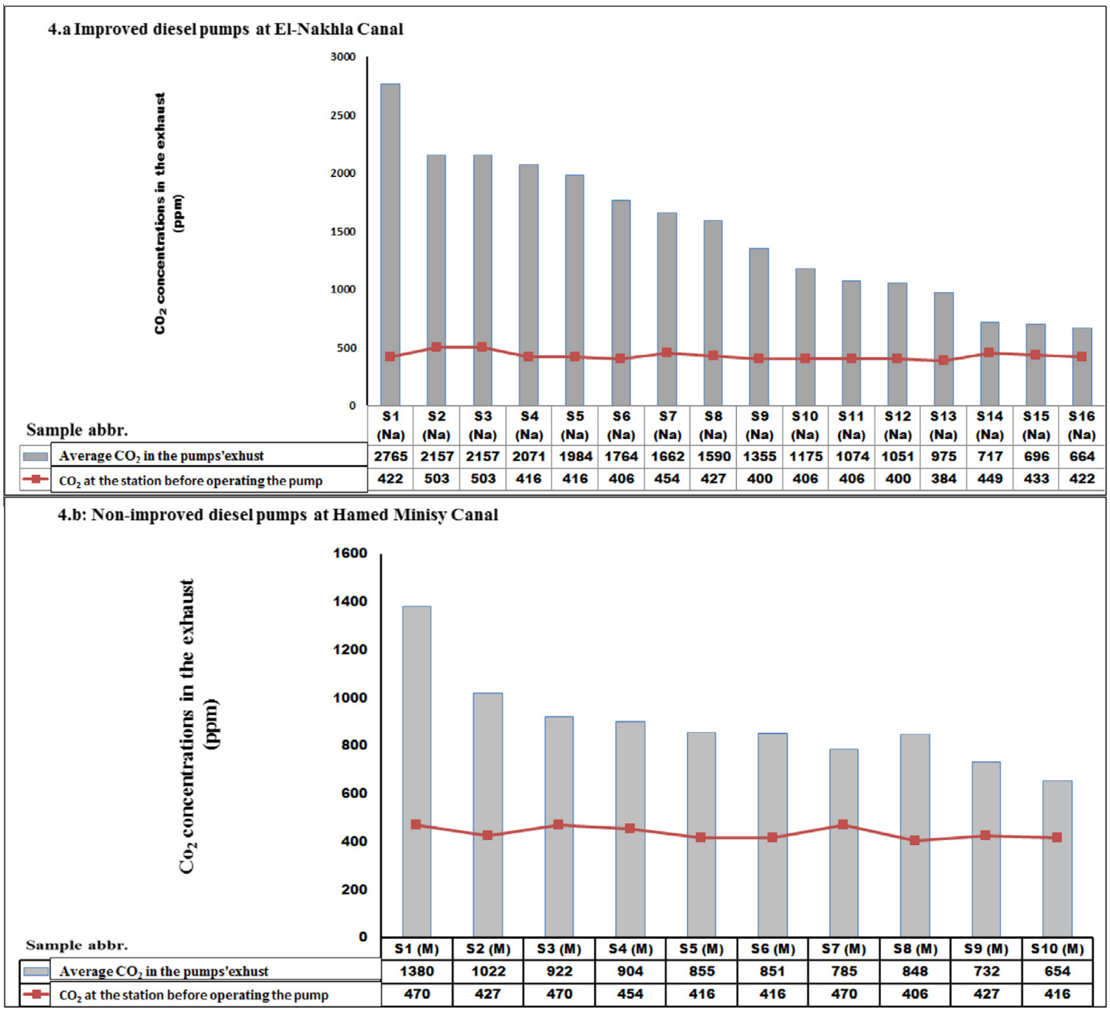

Figure 4 Measured and averaged CO_2 concentration in the exhaust of on-farm diesel pumps at the study areas.

average CO_2 emissions per ha served by the pumps at Nekla canal are 0.17 tCO_2/ha.

5.2. Comparative analysis of diesel and electrical pumps at the study areas

5.2.1. The environmental comparison

5.2.1.1. CO_2 emission at the field. At the field, as shown in Table 4, the highest CO_2 concentration in the exhaust of the pumps is that of the diesel pumps at El-Nakhla canal with value 1491 ppm. The CO_2 concentration in the exhaust of the pumps at El-Nakhla canal is higher than that of the pumps at Hamed Minisy canals by about 596 ppm. In general, the average CO_2 concentration in the exhaust of the diesel pumps is 1193 ppm. The electrical pumps at Nekla canal have zero emission at the field.

5.2.1.2. CO_2 emission per unit volume of water. According to the CO_2 emission per unit volume of water, as shown in Table 4, the pumps at Hamed Minisy are considered the highest ones with an average value 1.11 $kgCO_2$ which is higher than that of El-Nakhla and Nekla canals by about 0.24 and 1.08 $kgCO_2$ respectively. In general, the average CO_2 emission per unit volume of water pumped by diesel pumps is 0.99 $kgCO_2/m^3$ with S.D. $\pm$ 0.25, while the average CO_2 emission per unit volume of water pumped by electrical pumps is 0.02 $kgCO_2/m^3$ with S.D. $\pm$ 0.01.

5.2.1.3. CO_2 emission per unit of cultivate area. The highest CO_2 per ha of different crops is irrigated by diesel pumps at Hamed Minisy canal, as shown in Fig. 6a. In general, the average CO_2 emission per ha of wheat, maize, rice, long clover, broad bean, vegetables, cotton, and sugar beet irrigated by diesel pumps is higher than that of electrical pumps, as shown in Fig. 6b, by about 3.68, 6.21, 13.58, 6.15, 2.86, 6.35, 7.04, and 5.17 tCO_2/ha respectively. In the study area, the average CO_2 emission per ha served by on-farm diesel pumps is 6.55 tCO_2/ha, while the average CO_2 emission per ha served by on-farm electrical pumps is 0.17 tCO_2/ha.

5.2.2. The economic comparison

According to the analysis of the questionnaire, the energy cost of operating the non-improved diesel pumps at Hamed Minisy is considered the highest ones with an average value of 114 \$/ha/year (\$ = 7.5 LE) which is higher than that of the improved diesel and electrical pumps at El-Nakhla and Nekla canals by about 37 and 71 \$/ha/year respectively, as shown in

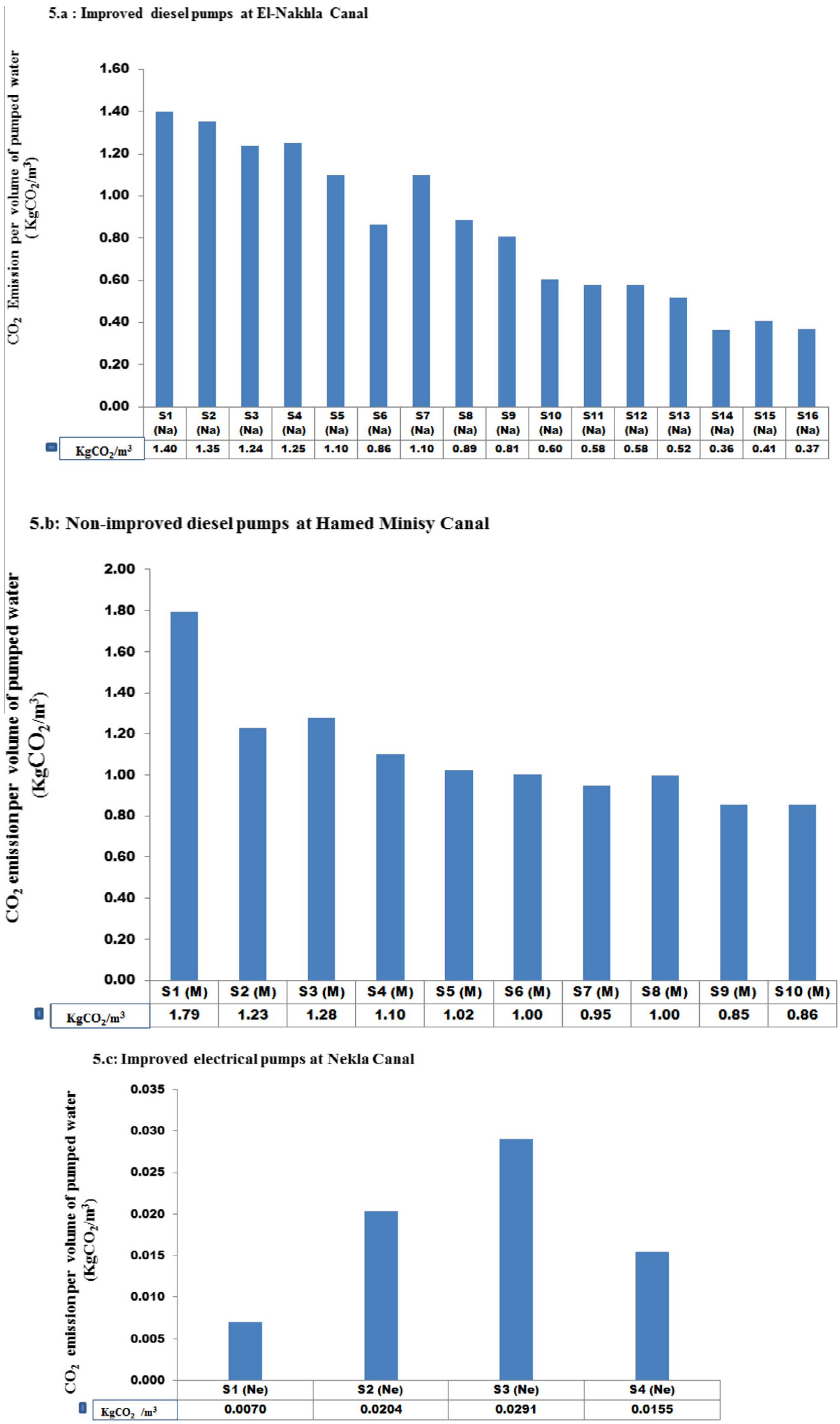

Figure 5 CO_2 emissions per volume of water emitted from the on-farm pumps at the study areas.

Table 3 Calculated CO_2 emissions per ha of the main crops at the study areas.

Pump	CO_2 emission (tCO_2/ha)							
	Wheat	Maize	Rice	Long-clover	Broad bean	Vegetables	Cotton	Sugar beet
Improved diesel pumps at El-Nakhla canal								
S1 $_{(Na)}$	5.73	9.68	21.16	9.58	4.46	9.89	10.97	8.06
S2 $_{(Na)}$	5.54	9.35	20.45	9.26	4.31	9.56	10.60	7.79
S3 $_{(Na)}$	5.06	8.55	18.69	8.46	3.94	8.74	9.69	7.12
S4 $_{(Na)}$	5.13	8.66	18.93	8.57	3.99	8.85	9.82	7.21
S5 $_{(Na)}$	4.50	7.60	16.62	7.53	3.51	7.77	8.62	6.33
S6 $_{(Na)}$	3.53	5.96	13.02	5.90	2.75	6.09	6.75	4.96
S7 $_{(Na)}$	4.49	7.58	16.58	7.51	3.50	7.75	8.60	6.32
S8 $_{(Na)}$	3.63	6.12	13.38	6.06	2.82	6.25	6.94	5.10
S9 $_{(Na)}$	3.30	5.57	12.19	5.52	2.57	5.70	6.32	4.64
S10 $_{(Na)}$	2.47	4.17	9.11	4.13	1.92	4.26	4.72	3.47
S11 $_{(Na)}$	2.37	4.00	8.74	3.96	1.84	4.09	4.53	3.33
S12 $_{(Na)}$	2.36	3.99	8.72	3.95	1.84	4.07	4.52	3.32
S13 $_{(Na)}$	2.12	3.57	7.82	3.54	1.65	3.65	4.05	2.98
S14 $_{(Na)}$	1.49	2.51	5.50	2.49	1.16	2.57	2.85	2.09
S15 $_{(Na)}$	1.66	2.80	6.13	2.78	1.29	2.87	3.18	2.34
S16 $_{(Na)}$	1.50	2.54	5.55	2.52	1.17	2.60	2.88	2.12
Average	3.43	5.79	12.66	5.73	2.67	5.92	6.57	4.82
Min	1.49	2.51	5.50	2.49	1.16	2.57	2.85	2.09
Max	5.73	9.68	21.16	9.58	4.46	9.89	10.97	8.06
Non-improved diesel pumps at Hamed Minisy canal								
S1 $_{(M)}$	7.34	12.40	27.11	12.28	5.72	12.67	14.06	10.33
S2 $_{(M)}$	5.03	8.50	18.57	8.41	3.92	8.68	9.63	7.08
S3 $_{(M)}$	5.24	8.85	19.35	8.76	4.08	9.04	10.03	7.37
S4 $_{(M)}$	4.50	7.60	16.63	7.53	3.51	7.77	8.62	6.33
S5 $_{(M)}$	4.18	7.06	15.42	6.98	3.25	7.21	8.00	5.88
S6 $_{(M)}$	4.11	6.94	15.18	6.87	3.20	7.09	7.87	5.78
S7 $_{(M)}$	3.88	6.55	14.33	6.49	3.02	6.70	7.43	5.46
S8 $_{(M)}$	4.09	6.91	15.11	6.84	3.19	7.06	7.83	5.76
S9 $_{(M)}$	3.50	5.90	12.90	5.84	2.72	6.03	6.69	4.92
S10 $_{(M)}$	3.50	5.91	12.93	5.85	2.73	6.04	6.70	4.93
Average	4.13	6.97	15.23	6.90	3.21	7.12	7.90	5.80
Min	3.50	5.90	12.90	5.84	2.72	6.03	6.69	4.92
Max	5.24	8.85	19.35	8.76	4.08	9.04	10.03	7.37
Improved electrical pumps at Nekhla canal								
S1 $_{(Ne)}$	0.10	0.17	0.38	0.17	0.08	0.18	0.20	0.15
S2 $_{(Ne)}$	0.08	0.14	0.31	0.14	0.06	0.14	0.16	0.12
S3 $_{(Ne)}$	0.12	0.20	0.44	0.20	0.09	0.21	0.23	0.17
S4 $_{(Ne)}$	0.06	0.11	0.23	0.11	0.05	0.11	0.12	0.09
Average of 52 pumps	0.10	0.17	0.37	0.17	0.08	0.17	0.19	0.14
Min	0.06	0.11	0.23	0.11	0.05	0.11	0.12	0.09
Max	0.12	0.20	0.44	0.20	0.09	0.21	0.23	0.17

Table 4. The cost of operation and maintenance of the pumps at Hamed Minisy canal is considered the highest ones with an average value 51 $/ha/year which is higher than that of El-Nakhla and Nekla canals by 13 and 35 $/ha/year respectively.

The significant difference of the energy cost and the operation and maintenance cost of the pumps at the three canals was determined by performing *t*-test. The results of the *t*-test were summarized in Table 5. The *P* value of the *t*-test that was performed to determine the significant difference between the cost of operation and maintenance of the diesel pumps at El-Nakhla and Hamed Minisy canal equals about 0.001. By conventional criteria, this difference is considered to be not statistically significant, while the *P* value of the *t*-test for the cost of energy for operating the pumps at the previous two canals was less than 0.0001. By conventional criteria, this difference is considered to be extremely statistically significant.

Moreover, another *t*-test was performed to determine the significant difference between the cost of energy and the cost of operation and maintenance of the diesel and electrical pumps at El-Nakhla and Nekla canals. The *P* value in this case for both the cost of energy and the cost of operation and maintenance was less than 0.0001. By conventional criteria, this difference is considered to be extremely statistically significant.

In general, the average cost of energy consumed for operating the diesel pumps and the electrical pumps is 96 and 43 $/ha/year. The operation and maintenance cost of the two types is 45 and 10 $/ha/year respectively. This result is slightly

Table 4 Compression among pumps at the three studied areas.

Canal		Cost of energy ($/ha/year)	Cost of O&M ($/ha/year)	CO_2 emission per unit volume of water (ppm)	CO_2 emission per unit volume of water ($kgCO_2/m^3$)	S.D.
El-Nakhla (Improved-diesel pump)	Average	78	38	1491	0.87	±0.35
	Max			2765	1.40	
	Min			696	0.36	
Hamed Minisy (Non-improved-diesel pump)	Average	114	51	895	1.11	±0.15
	Max			1022	1.28	
	Min			654	0.85	
Diesel						
	Average	**96**	**45**	**1193**	**0.99**	**±0.25**
	Max			**1894**	**1.34**	
	Min			**675**	**0.61**	
Electrical						
Nekla[b] (Electrical pump)	Average	**43**	**10**		**0.02**	**±0.002**
	Max				**0.03**	
	Min				**0.02**	

[a] $ = 7.5 LE (Central bank of Egypt, 2014).
[b] Co_2 emission is due to utilizing fuel at the electrical power plant.

higher than the values estimated by Nour el-din in 2005 [15]. Nour el-din in 2005 estimated the running cost of the diesel pumps and electrical pumps with values 86 and 36 $/ha/year respectively [15].

5.2.3. The social comparison

According to the analysis of the questionnaire, the satisfaction of the farmer with the pump's type was determined. The analysis showed that the farmer prefers the electrical pumps as they need less maintenance. The only complaint from the electrical pumps is that when the level of the water in the canal is low they cannot operate the pumps. On the other hand, the farmers complain that the diesel pumps need frequent maintenance. In addition, they complain from the high cost of fuel, oil, and the annual operation and maintenance of the diesel pumps.

5.3. CO_2 emission due to the current cropping pattern in the study areas

The cropping patterns at each of study areas were collected from Centralized Management of Land, Water, and the Environment (CMLWE) [16]. Wheat, maize, rice, cotton, long clover, vegetables, and sugar beet are the main cultivated crops at the three studied areas in year 2012–2013, as shown in Table 6. At El-Nakhla canal the cultivated area is 1095 ha and the total water consumed per year is 9 Mm^3. Pumping this quantity of water, results in producing 6390 tCO_2, as shown in Table 6. Pumping 41 Mm^3 of water for irrigating 5240 ha at Hamed Minisy releases 40,691 tCO_2. According to Nekla canal, lifting 19 Mm^3 of water for cultivating 2320 ha releases 461 tCO_2.

6. Conclusions and recommendations

Through the current study, a comparative analysis among three categories of on-farm irrigation pumps (non-improved diesel pumps, improved diesel pumps, and improved electrical pumps) in three study areas (El-Nakhla, Hamed Minisy, and Nekla canals) at El-Behera governorate in Egypt is carried out.

The comparative analysis was achieved by carrying out the following activities: (i) direct measuring the carbon dioxide resulting from utilizing 16 improved diesel pumps (pumps at El-Nakhla canal) and 10 non-improved diesel pumps (pumps at Hamed Minisy canal). The improved pumps serve canals and mesques that were improved by projects at Ministry of Water Resources and Irrigation of Egypt. The non-improved are private mobile diesel pumps owed by farmers, (ii) calculate the carbon dioxide emissions resulting from utilizing 52 improved electrical pumps (pumps at Nekla canal), (iii) carry out a comparative analysis among the previous pumps applying a set of environment, economic, and social indicators. The environmental indicators include CO_2 emitted from diesel pumps, CO_2 emitted at the power plants due to utilizing electrical pumps, CO_2 emission per unit volume of water, and CO_2 emission per ha. The economic indicators comprise the cost of operation and maintenance of the pumps and the cost of energy for operating the pump. The social indicator embraces the satisfaction of farmers with the pumps category, and (iv) analyze the carbon dioxide emissions due to the current cropping pattern at the study areas.

The study showed that according to the environmental evaluation, the average CO_2 emission per cubic meter of water pumped by non-improved diesel pumps, improved diesel pumps and improved electrical pumps is 1.11, 0.87, and 0.02 $kgCO_2/m^3$ respectively. The average CO_2 emissions per ha served by non-improved diesel pumps, improved diesel pumps and improved electrical pumps are 7.16, 5.95, and 0.17 tCO_2/ha respectively. In general, the average CO_2 emission per unit volume of water and the average CO_2 emission per ha served by diesel pumps are higher than that of electrical pumps by 0.96 $kgCO_2/m^3$ and 6.38 tCO_2/ha respectively.

According to the economic evaluation, the average cost of energy and operation and maintenance of the non-improved diesel pumps, improved diesel pumps and improved electrical pumps are 166, 116, and 52 $/ha/year respectively. According to the social evaluation, the study illustrated that the farmer prefers electrical pumps as they need less maintenance than

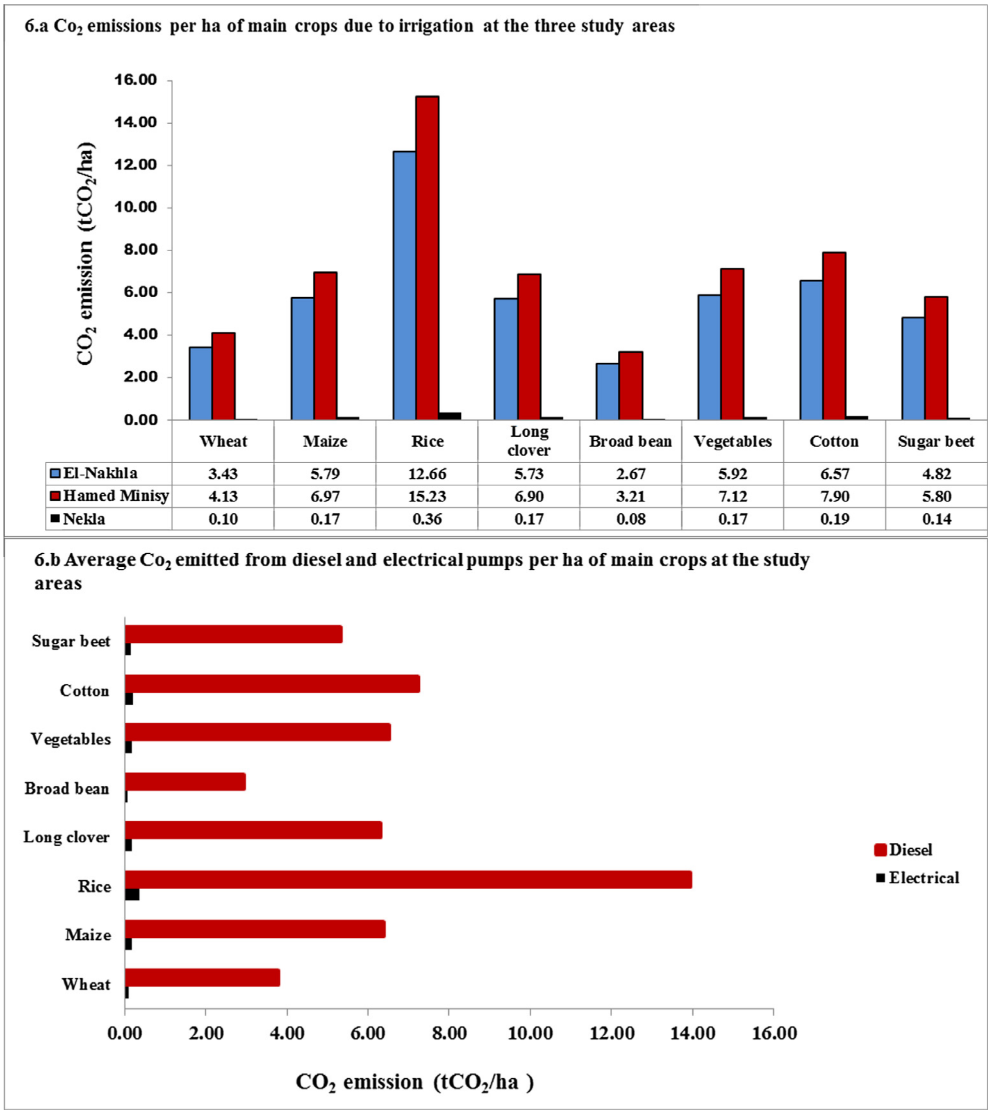

Figure 6 CO_2 emissions per hectares of main crops due to irrigation at the three studies areas.

Table 5 The significant difference of the energy cost and the operation and maintenance cost of the pumps at the study areas by Results of *t*-test.

	t-Test 1		*t*-Test-2		*t*-Test-3		Test-4	
	Energy cost		Operation and maintenance cost		Energy cost		Operation and maintenance cost	
	El-Nakhla	Hamed Minisy	El-Nakhla	Hamed Minisy	El-Nakhla	Nekla	El-Nakhla	Nekla
Mean	78	114	38	51	78	42	38	10
Variance	2.65	0.25	46.44	113.26	2.65	25.92	46.44	31.14
Observations	16	10	16	10	16	7	16	8
SD	1.57	0.48	6.60	10.10	1.57	4.71	6.60	5.22
df	24		24		21		22	
t Stat	−68.58		-3.83		25.63		10.38	
P	4.74E−29		0.001		2.51E−17		6.05E−10	
Standard error of difference	0.538		5.368		1.356		2.969	

the diesel pumps. In addition, they complain from the high cost of fuel, oil, and the annual operation and maintenance of the diesel pumps.

The study showed that, in 2012–2013, the CO_2 emission due to irrigating the cropping pattern at Hamed Minisy Canal is about 40,691 tCO_2 due to pumping 41 Mm^3 of water for

Table 6 Estimated CO_2 emission due to the current cropping pattern at the study areas in year 2012–2013.

Crop	Area (ha)	Water (Mm^3)	Carbon emission (t CO_{2e})
El-Nakhla			
Wheat	151	0.62	519
Maize	90	0.62	523
Rice	242	3.65	3058
Long-Clover	279	1.91	1602
Broad bean	29	0.09	61
Cotton	102	0.80	212
Vegetables	201	1.42	416
Total	1095	9.00	6390
Hamed Minisy			
Wheat	1895	07.76	7819
Maize	622	04.30	4330
Rice	1249	18.88	19,024
Long-Clover	1304	08.92	8991
Broad bean	110	00.35	365
Sugar beet	61	00.35	162
Total	5240	41.00	40,691
Nekla			
Wheat	623	2.55	62
Maize	194	1.34	33
Rice	636	9.62	235
Long-Clover	528	3.61	88
Broad bean	94	0.30	28
Cotton	245	1.92	14
Total	2320	19.00	461

irrigating 5240 ha. At El-Nakhla canal the cultivated area is 1095 ha and the total water consumed is about 9 Mm^3. Pumping this quantity of water, results in producing 6390 tCO_2. According to Nekla canal, pumping 19 Mm^3 for cultivating 2320 ha releases 509 tCO_2. From previous, in 2012–2013, the total CO_2 emission due to pumping 69 Mm^3 for irrigating the cropping pattern at the study areas was about 0.045 Mt CO_2.

From previous, it is concluded that the improved electrical pumps followed by the improved diesel pumps help in producing less CO_2 emission. In general, the electrical pumps are more environmentally, economically and socially efficient than the diesel pumps. The GHG emission intensity of irrigation depends essentially on the water use efficiency, and therefore improving water use efficiency (both technical and managerial) can be effectual in reducing emissions.

This paper is considered a step ahead for estimating the CO_2 emission all over the country from irrigation pumps, where the current paper studied the CO_2 emission on a micro-scale level (on-farm pumping irrigation) in pilot areas in Egypt. Estimating the CO_2 emission on a macro-scale level (the national scale) will be a repetitive work of this study. Developing national strategy for low-carbon economy and less energy use for irrigation is essential. Further study is recommended to study how to reduce the CO_2 emitted due to energy use for irrigation pumps at the study areas. It is recommended to extrapolate the current research to the national scale. Due to the limitation of energy resources in Egypt, it is recommended to study the applicability of applying alternate energy sources, such as wind and solar that results in providing clean energy with zero carbon dioxide emissions, for pumping water.

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