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Rehabilitation and upgrading wastewater treatment plant for safe irrigation reuse in remote area

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Abstract

This study presents an extensive evaluation of a full-scale sewage treatment system in a remote area with a population of 9,000 equivalents in Egypt. The present achievement can be implemented in several arid and semi-arid areas. Previously, this treatment system was heavily destroyed during the turmoil and became completely out of operation. Presently, the capacity of the treatment system increased from 345.5 to 648 m^3/d. The present rehabilitation, upgrading, and optimizing consisted of rebuilding the main construction system, addition of chemical coagulation/sedimentation, Gravel Bed Hydroponic Wetland (GBHW) followed by waste maturation pond at a surface area of 784 m^2. Results indicated that the overall removal of the pollution parameters namely: turbidity, total suspended solids (TSS), chemical oxygen demand (COD), Biological oxygen demand (BOD_5), and oil and grease were excellent (ranged between 96.9 to 99%). Further improvement was achieved by employing the maturation pond. In addition, successful removal of the nutrients elements in the final treated effluent reached 83.4% for total kjeldahl nitrogen (TKN), 99.3% for ammonia-nitrogen, 63.4% for organic nitrogen, and 59.8% for total phosphorous (TP). The pathogen removal was excellent, namely: faecal coliform and *E.coli*, where the overall removal reached 100% each (more than ten and six orders of magnitude). Meanwhile, the number of cells or eggs of Nimatoda (count/L) in the raw wastewater was also 100% removed in the final treated effluent.

Key words: gravel bed hydroponic wetlands, maturation pond, optimizing wastewater treatment plant, rehabilitation, safe irrigation reuse, upgrading

Highlights

- Overall removal of oil and grease was 96.9% to 99%.
- Overall removal of faecal coliform and *E.coli* reached 100% each.
- Nimatoda (count/L) was also 100% removed in the final treated effluent.
- This upgrading increased the capacity to receive a larger wastewater volume and increased the hydraulic retention time as well.
- GBHWs provide an effluent that meets the required limit standards for safe water reuse.

INTRODUCTION

Sewage wastewater contains, generally, several pollutants including human excreta that require a costly multi-step treatment to comply with the legislative requirements. The discharge of such inadequately treated wastewater results in the release of several physical, chemical, and micro-biological pollutants to the environment. The impact, therefore, is a great risk to public health, the quality of water, and the aquatic ecosystems (Schellekens *et al.* 2020). From the

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sustainability point of view, however, water reuse is well recognized as the key option to reduce water consumption (OECD 2020). Consequently, the reuse of water for agriculture purposes should be considered with great caution (Abdel-Shafy & El-Khateeb 2019). In this respect, there are certain requirements that regulate the quality of water reuse in irrigation that should be considered carefully to avoid any risk associated with human health hazard (United Nations 2019). These are the main barriers for safe water reuse in agriculture (Kim *et al.* 2013). Therefore, upgrading of wastewater treatment facilities may be necessary to meet the existing effluent quality as well as the strict effluent quality requirements. The quality of wastewater influent to wastewater treatment plants (WWTPs) can be greatly affected by population growth and/or sewer network expansions to serve more areas (Hahvi *et al.* 2006; Abdel-Shafy *et al.* 2011). The inability to meet the effluent quality could be a result of several factors including improper plant operation/maintenance, inadequate plant design as well as increased hydraulic or organic loading. The later may be caused by the change in wastewater flow or characteristics (Abdel-Shafy *et al.* 2011; WRRF 2011). Usually, the construction of the WWTPs is designed to ensure they can be operated for periods ranging from 20 to 60 years through two or three stages (Metcalf & Eddy 2005; Abdel-Shafy *et al.* 2011). Sometimes, the lifetime of the WWTPs is extended to last over 60 years. In many countries, the existing WWTPs are aging as a result of demanding more and better quality of treated wastewater, responding to the following factors: population growth, higher standards of safety, health, and environmental protection requirements. It is documented that health risks rise sharply according to the ingestion or reuse of unsafe treated wastewater for irrigation (Abdel-Shafy *et al.* 2008; Abdel-Shafy & El-Khateeb 2019). Several diseases related to wastewater sanitation are recorded and account for about 4.0% of all deaths and 5.8% of the total infectious disease occurring worldwide.

Great efforts have been conducted to upgrade the existing WWTPs processes by several researchers; most of them are feasible (Abdel-Shafy *et al.* 1996; Weber *et al.* 2007; El-Sheikh 2011). Chemical coagulants have been applied successfully to enhance the performance of existing WWTPs and to improve the quality of the produced sludge (De-Feo *et al.* 2008; El-Sheikh *et al.* 2010; Abdel-Shafy *et al.* 2019; Magwaza *et al.* 2020). Moreover, cost-effective natural wastewater treatment processes such as constructed wetlands (CWs), oxidation ponds, maturation ponds, lagoons and anaerobic processes have been also implemented for the same purposes (Masi *et al.* 2010; Abdel-Shafy & Al-Sulaiman 2014; Abdel-Shafy *et al.* 2017). Therefore, the upgrading and optimizing of dated WWTPs is essential to meet the new effluent standards while considering the cost effectiveness within an economically responsible and environmentally sound framework (Abdel-Shafy & El-Khateeb 2013). Such upgrading can achieve the following benefits: allowing additional capacity in a given unit processes, reducing the energy consumption, improving the effluent quality, safe discharge and/or reuse of the treated water (Masi *et al.* 2008; Abdel-Shafy & Mansour 2018).

During the last 40–45 years, different types of Gravel Bed Hydroponic Wetland (GBHW) systems have been implemented and developed in many countries for wastewater treatment (Abdel-Shafy & Dewedar 2012; Li *et al.* 2015; Magwaza *et al.* 2020). These technologies gained a wide acceptance as a wastewater treatment system due to many advantages, including low cost to construct, simplicity of build, very low consumption of energy or no energy use at all; and low cost of operation and maintenance. Therefore, they offer a feasible technology particularly in the arid and semi-arid developing countries like Egypt (Abdel-Shafy *et al.* 2009). The other advantages of GBHWs, as constructed wetlands (CWs), include being a highly stable system due to the high buffering capacities, and ability to tolerate different fluctuations in flow rate and inlet quality, while the sludge is only produced via the primary treatment stage (Crites & Tchobanoglous 1998; Regelsberger *et al.* 2007; Almuktar *et al.* 2015). As a result, the CWs have proved to be a highly efficient treatment system for handling different types of wastewater (WRRF 2011). The most applicable CW systems are the subsurface flow type (Masi *et al.* 2010; Almuktar *et al.* 2015). Meanwhile, CWs are capable of handling industrial wastewater, elimination of heavy metals as well as agricultural or agro-food wastewaters that are

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characterized by high organic load (Abdel-Shafy *et al.* 1986; Abdel-Shafy *et al.* 1994). Furthermore, CWs are also efficient in the removal of nutrient elements (nitrogen and phosphorous), micropollutants including persistent organic compounds, as well as eliminating heavy metals in the treated effluent (Vymazal 2001; Abdel-Shafy *et al.* 2013; Magwaza *et al.* 2020). The efficiency of the CWs depends, essentially, on several factors including surface area, bed length, depth, and water retention time. They also depend slightly on the type of hydrophytes, and the aggregate (Masi *et al.* 2008; WRRF 2011). CWs have also been employed for the treatment of blackwater and greywater separately (Abdel-Shafy *et al.* 2009). Furthermore, blackwater has been treated by hybrid wetlands using horizontal flow followed by a vertical flow system where very efficient removal was achieved (Abdel-Shafy *et al.* 2017). A field-scale GBHW with horizontal subsurface flow (HSSF) was constructed in a subtropical climate for the treatment of municipal wastewater (Abdel-Shafy & Dewedar 2012). It was concluded that the CWs are promising systems for wastewater treatment and safe reuse of the treated water in arid and semi-arid areas (Abdel-Shafy *et al.* 2009; Almuktar *et al.* 2015).

On the other hand, there is an increasing concern regarding the level of pathogens in treated sewage effluents, particularly for the reuse in irrigation or other non-potable purposes (EPA 2012; SWIM-SM 2013). In this respect, maturation ponds have proved to be efficient in pathogen removal. Nevertheless, maturation ponds impose substantial land requirements for construction. However, plug flow baffles or channels greatly prevent short circuiting. In addition, these channels improve the removal of faecal coliforms (FC) and other microbiological organisms as well as reducing the cost of investment and maintenance (Martínez *et al.* 2016; Dahl *et al.* 2017).

The main aim of the present investigation is to rehabilitate, upgrade, and optimize the treatment of domestic sewage water for unrestricted reuse. This study presents an extensive evaluation of a full-scale sewage treatment system of 9,000 population equivalents for the purpose of municipal wastewater treatment in a remote area of Egypt. The old treatment system was heavily destroyed. Currently, this system has been rehabilitated, upgraded, and optimized for sewage treatment and unrestricted reuse for agricultural purposes.

This study aimed to achieve four objectives: (i) to rehabilitate the old and heavily destroyed Gravel Bed Hydroponic Wetland (GBHW) for treatment of municipal wastewater; (ii) to upgrade the constructed wetland system to cope with the increased amount of received wastewater as a result of population increase on one hand and to improve the efficiency of treatment on the other hand; (iii) to add a maturation pond to the treatment system for the purpose of eliminating the pathogen contaminants in the wastewater; (iv) to meet the required characteristics for unrestricted water reuse for irrigation without any risk to public health.

Other important aims were: (i) protecting the environment from the impact of discharging untreated sewage; (ii) to increase the amount of water reuse for safe irrigation; (iii) to create new jobs for young people in this remote area; (iv) protecting public health by treating such a hazardous source of infected wastewater; (v) using an environmentally friendly treatment system to achieve the present goals.

MATERIALS AND METHODS

Description of the studied area

The studied regional area is a sandy plate form land in the desert with around 9,000 total populations as follows: about 4,000 in one village, and about 5,000 distributed in five small communities. The main activities include farming, hand-made crafts, school teachers, technical labor, workers; etc. The farming activities there depend on both groundwater and River Nile water. The latter is supplied by a small canal branched from the River Nile. There are no industrial activities in this area, therefore

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the present wastewater is mainly municipal type without any source of industrial influents. A gravel bed hydroponic wetland system (GBHW) was constructed and has been fully operational during the last 30 years for the treatment of municipal wastewater. At that time, the amount of such municipal wastewater was 345.5 m^3/d, and the population was around 4,800. The GBHW treatment system was heavily destroyed during the turmoil of January 2011. It had gone completely out of operation since that time. Presently, the amount of wastewater received increased to 648 m^3/d.

Treatment system before destruction and after rehabilitation/upgrading

The data is given in Table 1. The capacity of the treatment system, at present, increased from 345.5 to 648 m^3/d. The wastewater used to flow by gravity to six small receiving shallow sedimentation basins of 54 m^3 volume each through mechanical screening, controlled by six giant valves; each of these basins was split into two GBHW channels. These six sedimentation basins were recently reconstructed. The GBHW consists of 2% sloping channels lined with suitable impermeable membranes and filled with small gravel to provide a matrix in which hydrophytes can then be planted (Abdel-Shafy & Dewedar 2012). The effluent of the sedimentation chambers was introduced to the GBHW. After rehabilitation/upgrading, chemical coagulants were added to the raw wastewater inlet before the sedimentation basins. The effluent of the latter was introduced to the GBHW from the top of the beds in a horizontal flow through the channels to downstream by gravity, then to the maturation pond (Figure 1).

Table 1 | The GBH treatment system before and after rehabilitation, upgrading and optimizing

	Rehabilitation		
Description	**Before**	**After**	**Upgrading / optimizing**
Fence around the site	Partially destroyed	Repaired	Upgrading
Amount of wastewater (WW)	435.5 m^3 /d	648 m^3 /d	Receiving larger WW volume (optimizing)
Chemical coagulation	None	Added	Upgrading
Primary sedimentation basins	Partially destroyed	Rebuilt	Six basins, 54 m^3 each
Piping system	Destroyed	Replaced	Rehabilitation
Screens	Partially destroyed	Repaired	Rehabilitation
6 giant valves (the inlet of WW to GBH)	Disappeared	Replaced	Rehabilitation
12 GBH channels	Partially destroyed	Repaired	Rehabilitation
Length and width dimensions of the GBH (each channel)	100 * 2 * 0.4 m	120 * 2.5 * 0.9 m	Depth increased (receives larger WW volume) upgrading
GBH surface area m^2	2,400 m^2	3,600 m^2	Increased – upgrading
GBH (total volume) m^3	960 m^3	3,240 m^3	Increased – upgrading
Size of gravels in GBH	3–6 mm	2–4 mm	Upgrading
Maturation pond	None	Added	Added – optimizing
Maturation pond (surface area)	None	784 m^2	Added – optimizing
Maturation pond (total volume)	None	470 m^3	Added – optimizing
Use of treated effluent	Wasted by disposal to lake	Reuse for irrigation	Advantage – optimizing

The gravel bed hydroponic wetland (GBHW) before rehabilitation

The GBHW consisted of 12 channels. Before rehabilitation, each channel was 2.0 m wide, 100 m long, and 0.4 m deep at a slope of 2% to allow the flow of wastewater by gravity down to the end

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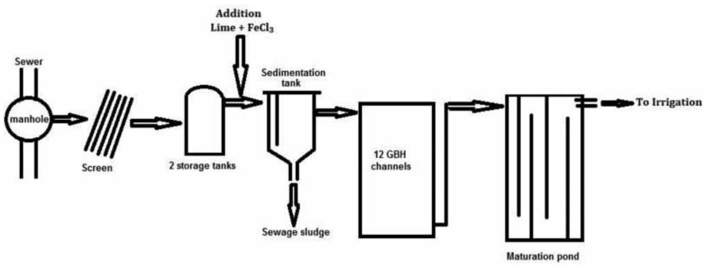

Figure 1 | Schematic diagram of the implemented wastewater treatment train.

of the channels (Table 1). Each channel was filled with 3–6 mm gravels. The GBHW channels were partially damaged.

Preliminary design of the treatment system

The capacity of the treatment plant is affected mainly by the construction cost (Magwaza *et al.* 2020; Schellekens *et al.* 2020). Presently, the capacity of 9,000 equivalent populations was chosen according to the following calculation:

The amount of the received raw municipal wastewater is:

$$Q = 9,000\,\text{persons} \times 90\ \text{l/cap/day} = 810,000\,\text{l/d}$$

Sewage factor flow = 80%

Amount of sewage = 0.80 × 810,000 = 648,000 l/d = 648 m^3/d

There was no wastewater flow at night. Therefore, the inlet to the GBHW was turned off from 1:00 am till 6:00 am. This allows the GBHW to receive atmospheric air as an attempt to create an aerobic condition in this system during such periods. Therefore, the average flow rate during these 19 hours was 23.4 m^3/sec.

Rehabilitation of the treatment system

Description of the site

Table 1 presents the details of the employed successive works in the treatment systems, namely rehabilitation, upgrading and optimization of sewage wastewater treatment in the studied remote area. The train of the implemented treatment system consists of the following: screening, chemical coagulation, sedimentation, GBHW, and a maturation pond (Figure 1). The final treated effluent is planned to be reused for safe irrigation.

The concept of the rehabilitation and upgrading is summarized as follows:

Screening: to remove the bulky materials and protect the water pumps from clogging by these bulky materials.

Storage equalization tanks: two tanks to equalize and to regulate the flow of the wastewater.

Screening and sedimentation basins: Screening was employed to eliminate any bulky materials. The storage tanks were important to equalize the raw wastewater where the outlet is distributed into three sedimentation basins (Figure 1). The total capacity of the basins was 150 m^3. Each one was divided by baffle into three smaller divisions as follows: the first partition was for degreasing, the second and third partitions were for settling as well as separating the sludge and the loaded particles from wastewater. The predetermined doses of lime in combination with ferric chloride were added to the first

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partition in each sedimentation basin. The total effective dimension of each chamber was 3 * 6* 3 m. The effluent of each chamber was directed to the receiving tank, which was equipped with a giant control valve. The flowing water from each receiving tank was divided into two. Each part was directed to flow horizontally through two channels of the GBHW (Figure 1).

Upgrading of the treatment system:

Gravel Bed Hydroponics Wetland (GBHW): After rehabilitation, the GBHW were reconstructed and redesigned to be as follows: 2.5 m wide, 120 m long, and 0.9 m deep at the same previous slope of 2% (Table 1). The bottom and sidewalls of each channels were artificially sealed and insulated by means of an impermeable layer of materials that are resistant to acid, roots, rodents, and alkali proof, non-toxic, and made of recyclable materials as recommended (Masi *et al.* 2004; Masi *et al.* 2008; Masi *et al.* 2010). The media was 2–4 mm gravel. These channels were planted with vascular plants, namely *Phragmites australis*.

Maturation Pond: The new maturation pond (volume 470 m^3, surface area 784 m^2), with the dimensions of 28 × 28 × 0.6 m, was laid out and constructed to receive the effluent of the GBHW (Figure 1).

A draft diagram of the implemented wastewater treatment train is illustrated in Figure 1.

Chemical coagulation

The raw wastewater was subjected to chemical coagulation, namely lime and ferric chloride. For the determination of the optimum dose of lime, a jar-test apparatus was employed. For this purpose, variable lime doses ranged from 10 to 80 mg/l were added to determine the optimum dose. The determined optimum lime dose was added in combination with 30 mg/l ferric chloride ($FeCl_3$) to each sedimentation basin to enhance the removal to the pollution parameters.

Physical, chemical, and biological characteristics of wastewater

Samples collection and examination

Reaching a steady state of the treatment system took about 5–6 months due to the seasonal variations, after which this sampling program was considered. Wastewater samples (20 liters each) were collected on a weekly basis from the following points: raw wastewater, the inlet and outlet samples from each sedimentation basin, GBHW channels, and the maturation pond. The sampling sites were selected to represent a wide range of successive treatment options. All samples were collected on the same day and in the same sequence of time between 10:00 and 12:00 am. The collected samples were taken directly to the laboratory for determination of the physical and chemical characteristics according to the Standard Methods (APHA 2012). This study was carried out for a period of 12 months through an extensive wastewater sampling program. The bacteriological characteristics were determined only for the raw wastewater inlet, the outlet of the GBHW, and final maturation ponds treated effluents. The efficiency of each treatment step was precisely evaluated.

Calculation of COD and BOD fractions

$COD_{(sol)}$ = COD filtered through membrane filter paper (0.45 μm),
$COD_{(col)}$ = COD of the filtrate from 4.4 μm filter paper – COD of the filtrate from membrane filter paper (0.45 μm),
$COD_{(sus)}$ = Total COD – COD of the filtrate from 4.4 μm filter paper.

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Calculation of the GBHW

The hydraulic retention time (HRT) and organic loading rate (OLR) for COD and BOD_5 were calculated according to Crites & Tchobanoglous (1998). These calculations were based on the following equations:

$$\mathrm{HRT} = (\mathrm{V} * \eta)/\mathrm{Q}$$

where V = volume of the GBHW treatment system, and Q = discharge flow (m^3/day).

Since, V = 120*12*2.5*0.9 = 3,240 m^3, and Q = 648 m^3/day

(HRT) t = hydraulic detention time (day).

$$Q = (A * d * \eta)/t$$

where:

A = total surface area (m^2), d = water depth of the system (m), and

η = porosity of the system (0.4).

By substituting in the equation: $Q = (A^* \, d^* \, \eta)/t$

(HRT) t = [(120*12)*2.5*0.9*0.4]/648

Therefore, HRT is 2.0 day

Meanwhile, $OLR = (C^* \, d^* \, \eta)/t$

$\mathrm{ORL}_{(BOD5)} = 294*0.9*0.4/2 = 52.92$ Kg/ha/d

$\mathrm{ORL}_{(COD)} = 592*0.9*0.4/2 = 106.56$ Kg/ha/d

RESULTS AND DISCUSSIONS

Raw wastewater

The characteristics of the studied raw wastewater (Table 2) indicated that it contains relatively high values of the pollution parameters. The level of total dissolved solids (TDS), total suspended solids (TSS), chemical oxygen demand (COD), biological oxygen demand (BOD), total nitrogen compounds (NKT), total phosphates (TP), and oil and grease was 621, 479.2, 1,186.1, 609.2, 101.7, 8.0, and 44.6 mg/l respectively (Table 2). Turbidity was 97 NTU. The BOD_5/COD ratio ranged from 0.51 to 0.54 at an average of 0.53. These values reflect the biodegradability of the studied wastewater (Abdel-Shafy *et al.* 2017).

Chemical coagulation bench scale study

The bench-scale study indicated that 80 mg/l of lime could achieve the best removal rate (Table 3). By adding 30 mg/l of ferric chloride in combination with the optimum lime dose (80 mg/l), the overall removal rate reached 76.9, 50.1, 49.1, 48.8, and 56.5% for TSS, COD, BOD_5, TKN, and oil and grease respectively.

Wastewater treatment plant

By implementing chemical coagulation followed by sedimentation to the wastewater, a considerable removal of turbidity and TSS to 74.6% and 76.9% respectively was achieved due to the settling of the larger particles (Table 4). Meanwhile, a reasonable removal of COD and BOD_5 at 50.1 and 51.7% successively was also reached (Table 4). As a result, the BOD_5/COD ratio slightly decreased to an average of 0.50. The removal of total nitrogen (TKN) and total phosphate (TP) was only 48.8, and

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Table 2 | Physical and chemical characteristics of the raw sewage wastewater

		Raw sewage wastewater		
Parameters	**N**	**Min**	**Max**	**Average ± STDV**
pH	49	7.2	7.6	7.4 ± 0.074
Turbidity (NTU) **	49	87	110	97 ± 1.94
EC (μmhos)	49	588	640	605 ± 12.1
TDS ($mg{\cdot}L^{-1}$) **	49	550	635	621 ± 13.2
TSS ($mg{\cdot}L^{-1}$)	49	420	510	479.2 ± 9.58
COD_{total} ($mg{\cdot}L^{-1}$)	49	1,099	1,210	1,186.1 ± 23.7
$COD_{soluble}$ ($mg{\cdot}L^{-1}$)	49	350	400	379.5 ± 7.6
BOD_5 ($mg{\cdot}L^{-1}$)	49	580	620	609.2 ± 14.2
Ammonia nitrogen ($mg{\cdot}L^{-1}$)	49	15	35	25.7 ± 0.52
TKN ($mg{\cdot}L^{-1}$)	49	88	115	101.7 ± 2.03
Organic nitrogen ($mg{\cdot}L^{-1}$)	49	20	40	33.6 ± 0.67
Nitrates ($mg{\cdot}L^{-1}$)	49	N.D.	N.D.	N.D.
Nitrites ($mg{\cdot}L^{-1}$)	49	0.08	0.2	0.1 ± 0.002
TP ($mg{\cdot}L^{-1}$)	49	6	12	8.0 ± 0.16
Oil and grease ($mg{\cdot}L^{-1}$)	49	30	50	44.6 ± 0.88
Faecal coliforms (CFU/100 ml)	24	4×10^{10}	7×10^{10}	5.6×10^{10} ± 0.11
E.coli count ($100.ml^{-1}$)	24	1.4	5	$3.5 x10^6$ ± 0.07
Number of cells or eggs of Nimatoda ($count.L^{-1}$)	24	2	7	4 ± 0.08

EC = Electric conductivity, **TDC** = Total dissolved solids.
TSS = Total suspended solids, **COD** = Chemical oxygen demand.
BOD = Biological oxygen demand, **TKN** = Total kjeldahl nitrogen.
TP = Total phosphate, **Min.** = Minimum.
Max. = Maximum, **STDV** = Standard deviation.

13.8% respectively (Table 4). The ratio of $COD_{soluble}/COD_{total}$ improved from 0.320 in the raw wastewater to 0.400 after chemical coagulation/sedimentation.

The precipitates were drained from the bottom of the sedimentation tanks, and transferred to the drying bed site. They were then naturally dried by sunlight in this sunny country. This drying process takes time according to the season (i.e. summer or winter). Parts of the dried materials are reused for the treatment of petroleum produced water to enhance oil recovery according to the procedure described by other researchers (Abdel-Shafy *et al.* 2020). Other parts are mixed with cement materials to produce bricks after different treatment process by the specialists. These bricks are used for construction.

Treatment with gravel bed hydroponic wetland (GBHW)

By subjecting the effluent of the sedimentation to the GBHW, a higher removal rate was achieved for turbidity, TSS, COD, BOD_5, NH_4-N, and oil and grease, namely 81.3, 77.3, 69.3, 73.9, 63.5 and 67.3% respectively (Table 4). Meanwhile, reasonable removal was reached for the other pollution parameters including total-KN, org-N, and total-P; their elimination reached 59.4, 46.3, and 47.5% successively. The corresponding concentration of turbidity, TSS, COD, BOD_5, NH_4-N, total-KN, org-N, total-P, and oil and grease reached 4.5 NTU, 25.1, 182.5, 76.8, 7.5, 21.2, 14.4, 3.6, and 6.3 mg/l respectively (Table 4). The ratio of $COD_{soluble}/COD_{total}$ increased from 0.400 to 0.510 as indication of the biodegradability of this wastewater. Furthermore, faecal coliform was reduced from 5.6×10^{10} (CFU/100 ml) in the raw wastewater to 3.2×10^1 in the GBHW effluent. Such good elimination of the given pollution parameters was achieved as a result of the combination of chemical coagulation,

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Table 3 | Bench-scale study on the effect of different lime doses and 30 mg/l ferric chloride on the treatment of sewage water

			After added lime											
			10 mg/l		**20 mg/l**		**40 mg/l**		**60 mg/l**		**80 mg/l**		**80 mg/l lime + 30 mg/l $FeCl_3$**	
Parameters	**Number of samples**	**Raw sewage water**	**Ave. conc.**	**% R**	**Ave. conc.**	**% R**	**Ave. conc.**	**% R**	**Ave. conc.**	**% R**	**Ave. conc.**	**% R**	**Ave. conc.**	**Overall % R**
TSS (mg·L^{-1})	7	479.2 (±9.58)	440.4 (±8.8)	8.1	379.7 (±7.6)	13.79	298.7 (±6.01)	21.34	211.5 (±4.2)	29.90	141.3 (±2.8)	33.2	110.7 (±2.2)	76.9
COD (mg O_2.L)	7	1,186.1 (±23.7)	1,151.7 (±23.03)	2.9	1,064.9 (±21.3)	7.54	944.6 (±18.8)	11.30	829.3 (±16.6)	12.21	672.6 (±13.5)	18.9	592.4 (±11.8)	50.1
BOD_5 (mg O_2.L)	7	609.2 (±14.2)	586.7 (±11.7)	3.7	586.7 (±11.7)	7.53	513.9 (±10.3)	12.40	450.8 (±9.01)	12.27	372.2 (±7.4)	17.44	310.2 (±6.2)	49.1
Total N_2 (mg·L^{-1})	7	101.67 (±2.02)	96.0 (±2.02)	5.6	88.4 (±1.7)	7.9	81.2 (±1.6)	8.2	72.3 (±1.4)	10.9	63.3 (±1.3)	12.5	52.1 (±1.04)	48.8
Oil & Grease (mg·L^{-1})	7	44.6 (±0.88)	43.7 (±0.87)	2.0	40.5 (±0.81)	7.4	36.0 (±0.72)	11.1	29.2 (±0.58)	18.65	22.0 (±0.44)	24.7	19.4 (±0.38)	56.5

Ave. Conc. = average concentration, **% R** = Percentage of removal.

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Table 4 | Physical and chemical characteristics of the municipal wastewater via different treatment techniques including chemical coagulation, sedimentation, GBHW, and waste maturation pond

			80 mg/l lime and 30 mg/l $FeCl_3$ Sedimentation (average ± STDV)		GBHW Effluent (average ± STDV)		Maturation pond effluent (average ± STDV)			
Parameters	**N**	**Raw WW (average ± STDV)**	**Conc.**	**%R**	**Conc.**	**%R**	**Conc.**	**%R**	**Overall %R**	**Permissible limits***
pH	49	7.4 ± 0.074	8.1 ± 0.16	–	7.6 ± 0.15	–	7.6 ± 0.15	–	–	–
Turbidity (NTU) **	49	97 ± 1.94	24 ± 0.48	74.6	4.5 ± 0.09	81.3	0.71 ± 0.01	84.2	99.3	–
EC (μmhos)	49	605 ± 12.1	514.9 ± 10.3	14.9	330.6 ± 6.6	35.8	237.0 ± 4.74	28.3	60.8	250
TDS ($mg{\cdot}L^{-1}$) **	49	621 ± 13.2	598.0 ± 12	3.7	540.0 ± 10.8	9.7	433.3 ± 9.3	19.8	32. 3	2,000
TSS ($mg{\cdot}L^{-1}$)	49	479.2 ± 9.58	110.7 ± 2.2	76.9	25.1 ± 0.5	77.3	16.6 ± 0.33	33.7	96.5	20
CODtotal ($mg{\cdot}L^{-1}$)	49	1,186.1 ± 23.7	592.4 ± 11.85	50.1	182.5 ± 3.7	69.3	37.8 ± 0.76	79.3	96.8	40
CODsoluble ($mg{\cdot}L^{-1}$)	49	379.5 ± 7.6	236.8 ± 4.74	37.6	93.1 ± 1.86	60.7	22.8 ± 0.46	75.5	94.0	–
BOD_5 ($mg{\cdot}L^{-1}$)	49	609.2 ± 14.2	294.2 ± 5.88	51.7	72.8 ± 1.54	75.3	8.8 ± 0.38	87.9	98.6	20
Ammonia N ($mg{\cdot}L^{-1}$)	49	25.7 ± 0.52	20.64 ± 0.41	19.7	7.5 ± 0.15	63.5	0.17 ± 0.02	97.7	99.3	–
TKN ($mg{\cdot}L^{-1}$)	49	101.7 ± 2.03	52.1 ± 1.04	48.8	21.2 ± 0.43	59.4	16.9 ± 0.34	20.3	83.4	–
Organic N ($mg{\cdot}L^{-1}$)	49	33.6 ± 0.67	26.8 ± 0.54	20.3	14.4 ± 0.3	46.3	12.3 ± 0.25	14.6	63.4	–
Nitrates N ($mg{\cdot}L^{-1}$)	49	N.D.	0.8 ± 0.02	–	0.4 ± 0.008	–	0.6 ± 0.01	–	–	–
Nitrites ($mg{\cdot}L^{-1}$)	49	0.1 ± 0.002	0	100	–	–	–	–	–	–
TP ($mg{\cdot}L^{-1}$)	49	8.0 ± 0.16	6.9 ± 0.14	13.8	3.6 ± 0.07	47.5	2.9 ± 0.06	19.5	59.8	–
Oil & Grease ($mg{\cdot}L^{-1}$)	49	44.6 ± 0.88	19.4 ± 0.4	56.5	6.3 ± 0.13	67.3	1.4 ± 0.03	78.5	96.9	5
Faecal coliform (CFU/100 ml)	24	5.6×10^{10} ± 0.11	ND		3.2×10^{1}		Nil			
E.coli count ($100.ml^{-1}$)	24	$\mathbf{3.5 \times 10^{6}}$ ± 0.07	ND		ND		Nil			
Number of cells or eggs of Nimatoda Count/L	24	4 ± 0.08	ND		ND		zero			

GBHW = Gravel Bed Hydroponic Wetland, **N** = number of samples; **Con.** = concentration; **%R** = percentage of removal, **N.D.** = not detected,.

***Egyptian Guideline** = Egyptian code no. 501, 2005 for the reuse of treated wastewater in agriculture: ministry of housing, utilities and new communities [Egyptian code no. (501), 2005].

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sedimentation, and GBHW at the long hydraulic retention time, namely 2.0 days duration. However, increasing the detention time increased water losses to about 20 to 22% in this sunny and humid country. In addition, the combination of both condensed distribution of the hydrophyte roots down to 0.9 m depth, and gravel media of the GBHW system (at smaller size of 2–4 mm) were the additional tools to achieve the removal of the concerned pollution parameters (Abdel-Shafy & Dewedar 2012; Abdel-Shafy *et al.* 2017; Magwaza *et al.* 2020). On the other hand, the upgrading of the GBHW volume from 960 to 3,240 m^3 and the surface area from 2,400 to 3,600 m^2 (Table 5) allowed sufficient contact and penetration of air to the system during night to that enhance the elimination of ammonia, nitrites (Abdel-Shafy *et al.* 2017; Abdel-Shafy & Mansour 2018). The presence of healthy *Phragmites australis* plant was capable to of consuming a reasonable amount of the available nitrogen and phosphate compounds as nutrients from wastewater to the plants in the GBHW (Abdel-Shafy *et al.* 1986).

Table 5 | Dimensions of the sedimentation tanks, the horizontal and vertical wetlands

Unit	No of units	Length (m)	Width (m)	Depth (m)	Total surface area (m^2)	Total volume (m^3)	Filling media	Plant
SB	6	6	3	3	–		–	–
GBHW	12	120	2.5	0.90	3,600	3,240	Gravel	Phragmites
WMP	1	28	28	0.60	784		–	

Note: **SB** = Sedimentation basin, **GBHW** = Gravel Bed Hydroponic Wetland, **WMP** = Waste Maturation Pond.

Treatment with waste maturation pond (WSP)

Maturation ponds are a type of waste stabilization pond (WSP) designed for wastewater treatment mainly to reduce nutrients, pathogens, and carbon in the final stages of a WSP (Dahl *et al.* 2017). By submitting the effluent of the GBHW to the MP, further improvement was achieved with respect to the physical and chemical characteristics of the treated wastewater (Table 4). The removal rate of turbidity, TSS, COD, BOD_5, NH_4-N, TN, org-N, TP, and oil and grease reached 84.2, 37.7, 79.3, 87.9, 97.7, 20.3, 14.6, 19.5, and 78.5% respectively. The corresponding level of these parameters were 0.71 NTU, 16.6, 37.8, 8.8, 0.17, 16.9, 12.3, 2.9, and 1.4 mg/l. The ratio of $COD_{soluble}/COD_{total}$ improved from 0.510 to 0.603 (Table 4).

By implementing the given successive treatment techniques, the overall elimination of the studied pollution parameters reached 99.3, 96.5, 98.6, 98.6, 99.3, 83.4, 63.4, 59.8, and 96.9% for the turbidity, TSS, COD, BOD_5, NH_4-N, TN, org-N, TP, and oil and grease, respectively (Table 4). The overall improvement of the $COD_{soluble}/COD_{total}$ ratio increased from 0.320 in the raw wastewater to 0.603 in the final treated water as indication of successful treatment techniques. It is worth noting that the turbidity reached 0.71 NTU in the final effluent (lower than turbidity limit of drinking water 0.71 versus 1 NTU).

The pathogen removal was excellent where the faecal coliform (CFU/100 ml) and the *E.coli* count (100/ml) in the raw wastewater was 5.6×10^{10} and $3.5 x10^6$ respectively, they totally disappeared and were undetected in the final effluent as an indication of complete removal (Table 4). Meanwhile, the Number of cells or eggs of Nimatoda Count/L in the raw wastewater was 4; it became zero in the final treated effluent; as indication also of complete removal (Table 4).

DISCUSSIONS

The overall performance of the studied wastewater treatment system was excellent. Results (Tables 3 and 4) indicated that the combination of studied treatment systems was very efficient for the overall

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removal of the pollution parameters, namely turbidity, TSS, COD, BOD_5, and oil and grease (Table 4). Such efficiency is due to employing a well-designed and successful combination of chemical coagulation, sedimentation, GBHW, and a maturation pond (Figure 1). The highest efficiency of treatment was achieved by the GBHW (Table 4), where values of the HRT, $ORL_{(COD)}$, and $ORL_{(BOD)}$ were 2.0 day, 106.56 kg/ha/d, and 52.92 kg/ha/d, respectively. Further improvement was achieved by using the maturation pond (Table 4).

In addition, the nutrient elements were successfully removed, where the overall removal rate in the final effluent reached 83.4% of the TKN (from 101.7 to 16.9 mg/l); 99.3% of the ammonia-nitrogen (from 25.7 to 0.17 mg/l); 63.4% of the organic nitrogen (from 33.6 to 12.3 mg/l) and 59.8% of TP (from 8.0 mg/l to 2.9 mg/l) (Table 4). Such efficiency in the removal could be attributed to the combination of successful treatment systems including the natural oxidation of WMP over a surface area of 784 m^2 (Abdel-Shafy & Dewedar 2012; Abdel-Shafy *et al.* 2017; Magwaza *et al.* 2020).

Meanwhile, the excellent performance of the GBHW refers mainly to the relatively low velocity of the wastewater flow and the high surface area of the gravel media. Such media act as a gravel filter that provides opportunities for TSS sedimentation as well as adsorption on the biomass film adhered to the gravel media and the plant root system. The latter is also responsible for the reduction of the sludge in the wastewater.

The pathogen removal was excellent: faecal coliform and *E.coli* counts (100/ml) in the raw wastewater were 5.6×10^{10} and 3.5×10^6, respectively. The pathogens disappeared and were not detected in the final treated effluent as an indication of complete removal (Table 4). Similarly, the number of cells or eggs of Nimatoda (count/L) in the raw wastewater was 4, they were completely undetected in the final treated effluent. Many studies have been conducted to identify the principal factors involved in bacterial reduction in relation to the retention time (Lloyd *et al.* 2002). It was confirmed that exposing wastewater to the long retention time in the GBHW, followed by sunlight, visible light, or ultraviolet (UV) light and temperature in the waste maturation pond were very effective tools to eliminate the pathogens in sewage treated effluents (Magwaza *et al.* 2020).

The final treated effluent became within the very high quality that meets the permissible level of water reuse regulations according to the international and local limits, namely: FAO (2003), US-EPA (2012), WHO (2006), Egypt Amendment of law 48/1982 (2013) (Table 6).

CONCLUSIONS

The overall results of the present investigation reveal that the rehabilitation and upgrading of the old and partially destroyed GBHW was successfully achieved according to the present study. Employing additional factors including chemical coagulation and a maturation pond successfully enhanced the treatment performance and upgrading of the treatment system.

Thereby, longer detention time was obtained to end up with an effluent of higher quality. Certain nutrients were taken up by the plant biomass including nitrates, phosphates, potassium, and certain metals.

The constructed wetlands can be implemented at any scale with the minimum energy requirement, enabling a decentralized approach for the treatment of wastewater. The final treated effluent can be reused for agricultural irrigation and nutrient recycling. The drawback of the CWs is the required land area for construction. However, in the Middle East and North African countries, where the water issue is a stinging problem due to the deficiency of water resources, and continuous increase in population, the only solution is recycling of water by using simple, low cost, low energy techniques. There are many remote cities surrounded by vast desert areas suitable for wetlands construction and recycling of the treated effluent as a promising decentralized treatment facility.

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Table 6 | Guidelines and regulations for treated wastewater reuse in food crop irrigation

Parameter	Unit	WHO [46]	FAO [44]	US – EPA [45]	Egypt [47]
EC	μs/cm	–	<700	≤ 700	≤ 250
pH	–	–	6.5–8.4	6–9	6.5–8.5
TSS	$mg \cdot L^{-1}$	–	10	–	≤ 20
TDS	$mg \cdot L^{-1}$	–	<450	–	2,000
BOD	$mg \cdot L^{-1}$	–	10	≤ 10	≤ 20
COD	$mg \cdot L^{-1}$	–	–	–	≤ 40
T-P	$mg \cdot L^{-1}$	–	–	–	
T-N	$mg \cdot L^{-1}$	–	–	–	
Nitrate (NO_3-N)	$mg \cdot L^{-1}$	–	< 5	–	–
Ammonia-N	$mg \cdot L^{-1}$	–	–	–	
Oil and grease		–	–	–	5
Total coliforms	Per 100 ml	–	–	–	–
Fecal coliforms	Per 100 ml	$\leq 1,000$	5	ND	ND
E. coli	Per 100 ml	$\leq 1,000$	–	–	–
Intestinal nematodes	Per L	≤ 1	–	–	ND

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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