SSRG International Journal of Civil Engineering
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V11I8P108

Volume 11 Issue 8, 93-100, August 2024

Original Article

Evaluation of Ultra-Filtration Technique in Water Purification Compared to Conventional Techniques in Egypt

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Received: 09 June 2024 Revised: 17 July 2024 Accepted: 08 August 2024 Published: 29 August 2024

Abstract *- This paper evaluates Ultrafiltration (UF) technology for drinking water purification against conventional methods, using data from two plants in Qena, Upper Egypt: Nagaa Hamadi WPP (conventional) and Farshut WPP (UF). Both utilize the Nile River, ensuring a consistent comparison. Key parameters such as capital expenditure (CAPEX), Operational Expenditure (OPEX), water quality, water losses, and environmental impact were examined. The aim is to provide Egyptian stakeholders with insights into UF technology's cost-effectiveness, efficiency, and sustainability. Farshut WPP uses 48.57% less land than Nagaa Hamadi WPP and has construction costs only 5.72% higher. However, its operational cost is 1.11 times higher, at 0.8361 E£/m³ compared to 0.749314 E£/m³ at Nagaa Hamadi WPP. Chemical costs for UF are significantly higher, at 406.72% of conventional filtration costs. Despite these higher costs, Farshut WPP uses less electricity (0.36 kW/m³ versus 0.43 kW/m³) and produces higher-quality water with lower turbidity (0.01 NTU versus 0.23 NTU). The findings suggest that UF technology offers improved water quality and lower long-term operational costs despite higher initial and chemical costs. The paper recommends adopting UF technology in Upper Egypt's water infrastructure.*

Keywords *- Cost analysis, Drinking/Potable water production, Membrane technology, Ultra-Filtration, Water purification.*

1. Introduction

The traditional method of purifying water involves pumping water from its source to a water purification plant, where it undergoes several processes such as screening, coagulation, flocculation, sedimentation, filtration, and disinfection using various chemicals or methods.[1, 2] This process consumes a lot of energy, requires a large footprint, uses harmful chemicals that negatively impact the environment and incurs high operational expenses. On the other side, Ultrafiltration (UF) technology is increasingly recognized in the water purification field for its efficiency and capacity to eliminate a wide array of contaminants.[3-6] Ultrafiltration (UF) membranes can come in several configurations, such as hollow fiber membranes, flat sheet membranes, tubular membranes, spiral wound membranes, and capillary membranes.[7-10] Utilizing semi-permeable membranes and the most common and used materials in the manufacture of these membranes are PES, PSU, PVDF, PAN and PP, with pore sizes ranging from 0.01 to 0.1 micrometers and TMP ranging from 0.50 to 4.00 bar.[11-13] UF systems effectively remove total suspended solids, bacteria, viruses, and certain dissolved substances.[14-17] Maintaining UF membranes requires regular cleaning processes: backwash is called Air Scrubbing and Reverse Filtration (ASRF), Chemically Enhanced Backwash (CEB) is called also Enhanced Flux Maintenance (EFM), and Clean-in-Place (CIP).[14, 18-21]

Backwash is a daily routine that reverses water flow through the membrane to flush out contaminants, maintaining permeability and performance. CEB is used when backwashing is not enough, adding chemicals like chlorine or acids to the backwash to remove natural organic matter and scaling, performed weekly or bi-weekly, and CIP is a thorough, monthly or quarterly cleaning using strong chemicals to restore membrane performance, addressing severe fouling issues. Regular maintenance with backwash, CEB, and CIP is crucial to prevent irreversible fouling, reduce costs, get the best performance and ensure consistent water quality, thereby extending the UF membranes' lifespan and efficiency.[10][17][22-24]

UF technology provides a sustainable and efficient solution for water purification, meeting the rising demand for clean water in various regions. [25-27]

Ultra-Filtration (UF) technology was introduced in Egypt's potable water production sector in the 1980s. By December 2021, the number of Water Purification Plants (WPPs) utilizing UF had reached 32 WPPs, and it is now likely that this number has grown to over 50 WPPs. [28]

While UF technology has been expanding rapidly in Egypt, with many WPPs operating efficiently, some plants still encounter significant issues and operational challenges. To date, the UF technology has not been thoroughly evaluated or compared with traditional purification methods in Egypt. A comprehensive study is needed to provide decision-makers and stakeholders with insights into the technology, including its construction and operating costs, as well as its environmental impact. This would help optimize the application of UF technology by addressing the problems in existing UF WPPs and ensuring that new UF WPPs are built to avoid past issues, achieve maximum efficiency, and minimize costs. Additionally, it is crucial to ensure that UF technology is as environmentally friendly as possible and to determine under which conditions UF is the best option for water purification.

2. Materials and Methods

2.1. General

This study aims to comprehensively and fairly evaluate Ultrafiltration (UF) technology in water purification compared to traditional methods used in Egypt. The evaluation involves a detailed comparison of Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) for both systems, assessing raw and treated water quality, water losses, and system performance. Key parameters are identified and analyzed to ensure accurate and comprehensive comparisons.

The study also examines operational performance, design versus actual capacity, and environmental impact to determine the sustainability of each system. Proper identification and measurement of all relevant parameters are crucial to avoid incomplete comparisons and unfair evaluations.

A primary objective is to identify scenarios where UF Water Purification Plants (WPPs) are optimal and when pretreatment is needed for peak performance. The study aims to find the most effective pretreatment methods to enhance UF efficiency with minimal CAPEX and OPEX, reduced environmental impact, and improved sustainability.

Ultimately, the study provides stakeholders and decision-makers in Egypt with detailed information on UF WPPs, helping them decide if UF technology can financially and technically compete with traditional systems and offer a more sustainable and environmentally friendly approach to producing potable water.

Collecting data from various Water Purification Plants (WPPs) is essential for accurate and fair comparisons between Ultrafiltration (UF) and conventional water purification systems.

Key comparison points and mandatory parameters must be identified and clearly defined. The comparison should focus on technical and financial performance, environmental impact, and sustainability of both UF and conventional WPPs to ensure a comprehensive and fair evaluation.

2.2. CAPEX

CAPEX (indication for the capital costs) included construction cost, footprint area in which the WPP built it, electromechanical equipment cost and modules cost.

2.3. OPEX

OPEX (indication for the operational costs) included the energy consumption cost, maintenance cost, cleaning chemicals cost, coagulant cost and labor fees.

2.4. Water Quality

Water Quality of both raw water and product water from the two different purification systems included turbidity, inorganic analysis and microbiology analysis.

2.5. Water Losses

Water Losses including recovery %, design capacity, actual capacity, the quantity of water needed for the backwash, and the amount of water for circulation (cross-flow UF modules), are important indications of WPP's performance.

2.6. Environmental Impact and Sustainability

Environmental Impact and Sustainability included sludge characteristics from conventional WPPs and UF WPPs (quantity, method of disposal, ability of recycling, disposal point and chemicals existing in sludge).

3. Results and Discussion

The operational, analytical, financial, and technical data from both purification plants have been collected, compiled, and presented in tables and graphs. This data provides a valuable comparison between Ultrafiltration (UF) and conventional systems across five key categories: Capital Expenditure (CAPEX), Operational Expenditure (OPEX), water quality, water losses, and environmental impact and sustainability**.**

3.1. CAPEX

Capital Expenditure (CAPEX) includes the costs of acquiring fixed assets necessary for water purification systems, such as structures, equipment, and control panels. Nagaa Hamadi WPP, was built in 1999, cost approximately E£ 20,000,000, while Farshut WPP, constructed in 2019, cost about E£ 270,000,000. Adjusting for inflation, the estimated 2024 cost for Nagaa Hamadi WPP would be E£ 268,571,428.6, whereas Farshut WPP's cost in 2024 was significantly higher at E£ 746,470,588.2. This aligns with the general trend that membrane systems have higher capital costs than conventional systems.

Farshut WPP required significantly less land, only 73.53% of what the Nagaa Hamadi WPP needed to produce 1 m³ of treated water. When normalizing construction and land costs relative to treatment capacity, Farshut WPP's construction cost is only 5.72% higher than Nagaa Hamadi WPP for producing 1 m³ of treated water.

Table 1. Main key categories (comparison items) and their main parameters

CAPEX	OPEX	Water quality	Water losses	Environmental impact and sustainability
Footprint and land costs	Consumption of electricity and its costs	Quality of raw water	Design capacity	Chemicals existing in sludge
Construction costs	Salaries & Wages	Quality of product water	Actual capacity	Amount of consumed electricity
Electromechanical equipment costs	Chemicals costs	---	Recovery%	---
UF modules costs	Maintenance and repair costs	---	Quantity of needed water for backwash and chemical cleaning	---

The decreasing cost of UF membranes and reduced land requirements make UF systems more feasible for large-scale implementation, particularly in urban areas with high land prices, where CAPEX for UF systems can be lower than for conventional systems.

3.2. OPEX

Operational Expenditure (OPEX) covers the costs of running a water purification plant to achieve the desired drinking water quality and quantity, primarily involving expenses for chemicals and energy (electricity). In the studied plants, chemicals are used for coagulation, flocculation, and disinfection in the Nagaa Hamadi WPP, and for cleaning the UF membrane and disinfection in Farshut WPP. Nagaa Hamadi uses aluminium sulfate as a coagulant.

Both conventional and UF systems require rotating mechanical equipment like pumps, air blowers, and compressors. UF systems are more energy-intensive and costlier to operate, especially when raw water quality is good and low turbidity. This results in higher OPEX for UF systems due to substantial chemical and energy costs.

Overall, Farshut WPP's operational cost is 1.11 times higher than Nagaa Hamadi WPP's, costing 0.8361 E£/m³ compared to 0.749314 E£/m³. Chemical costs for UF systems are significantly higher (406.72% of conventional media filtration), though no coagulants are needed, resulting in better filtrate quality. The higher electricity consumption in UF systems is due to the need for air blowers, large particle filters, and feed pumps to maintain higher pressures.

3.3. Water Quality

Water quality is crucial in environmental science and public health, encompassing the physical, chemical, and biological properties of water. It determines water's suitability for drinking, recreation, and industrial use. The turbidity of raw water is nearly identical for both Water Purification Plants (WPPs) since they source water from the same source (Nile River). However, the turbidity of treated water is lower in the UF WPP compared to the Nagaa Hamadi WPP.

In 2023, the average turbidity of raw water at Nagaa Hamadi WPP was 3.58 NTU, and at Farshut WPP, it was 3.56 NTU. The average turbidity of treated water at Nagaa Hamadi WPP was 0.23 NTU, while at Farshut WPP, it was 0.01 NTU. These results clearly demonstrate the superior efficiency of UF WPPs in reducing turbidity compared to conventional WPPs.

3.4. Water Losses

Sand filters at Nagaa Hamadi WPP require regular backwashing to remove trapped particles, resulting in significant water loss, approximately 6.56% of the total treated water volume. Additional water loss occurs during sludge removal, which varies based on the dewatering processes used.

At Farshut WPP, semi-permeable membranes filter out particles, bacteria, and other contaminants. These membranes undergo periodic cleaning through backwashing, Air Scrubbing and Reverse Filtration (ASRF), and chemical processes like Clean-in-Place (CIP) and Enhanced Flux Maintenance (EFM). Water loss at Farshut UF WPP is generally higher, around 8%, which is 1.2 times the loss at Nagaa Hamadi. Farshut WPP also produces a concentrate containing removed contaminants, contributing to overall water loss, though this constitutes only a small percentage of the treated water.

Nagaa Hamadi WPP has a water recovery rate of 93.44%, slightly higher than the 92% at Farshut WPP. In conventional systems like Nagaa Hamadi, frequent backwashing of sand filters and sludge handling impact water recovery efficiency, involving additional water use and loss.

3.5. Environmental Impact and Sustainability

The sludge from Farshut WPP is more concentrated but similar to the feed water, as no coagulants are used before filtration. In contrast, the sludge from Nagaa Hamadi WPP contains high levels of aluminum due to the use of aluminum sulfate as a coagulant. This aluminum content can cause health issues like Alzheimer's disease and mental retardation in children, making UF system sludge environmentally safer. Disposing of aluminum-rich sludge incurs additional costs, whereas UF sludge, free from chemical contaminants but with higher suspended solids, can be discharged downstream.

Sustainable water purification requires balancing commercial and environmental impacts while ensuring high-quality water. Farshut WPP consistently produces high-quality filtrate without coagulants despite higher water losses. UF system sludge, free from heavy metal residues, poses minimal environmental impact. The volume of cleaning chemicals used in UF systems is minimal compared to backwash water. Electricity usage in Nagaa Hamadi WPP system is approximately 0.43 kW/m³, whereas in Farshut WPP, it is about 0.36 kW/m³. Higher energy consumption can increase greenhouse gas emissions unless renewable energy sources are used. UF process is highly automated, requires minimal operator intervention, and occupies a small footprint.

4. Conclusion

The study aims to compare Ultrafiltration (UF) and conventional water purification methods in Egypt, focusing on financial, technical, sustainability and environmental impacts. Five key categories were analyzed. The Capital Expenditure (CAPEX) for Farshut WPP to produce 1 m³ of treated water is 5.72% higher than that of Nagaa Hamadi WPP. The footprint (m^2) required by Nagaa Hamadi WPP to produce 1 m³ of treated water is 1.36 that of Farshut WPP. The Operational Expenditure (OPEX) for Farshut WPP to produce 1 m³ of treated water is 1.11 times higher than that of Nagaa Hamadi WPP, even though salaries at Farshut WPP are significantly lower, amounting to 64.83% of the salaries at Nagaa Hamadi WPP. Water losses at Farshut WPP are 1.22 times greater than those at Nagaa Hamadi WPP. Revealing that UF systems have higher Capital Expenditure (CAPEX), Operational Expenditure (OPEX), maintenance costs, and water losses than conventional systems. However, UF systems could become more commercially viable with high land and chemical prices and reduced electricity costs through renewable energy.

UF systems offer advantages such as consistent, high-quality filtrate, smaller land requirements, non-toxic sludge discharge, and high automation with reduced manpower needs. Conventional systems face challenges like fluctuating water quality, precise coagulant dosage needs, and sludge contaminated with heavy metals. Despite higher initial and operational costs, UF systems provide sustainability benefits, including the elimination of coagulants and minimal environmental impact from sludge.

The study emphasizes the need for further research and case studies on similar industrial-scale water purification plants in different regions to support more comprehensive justifications. While UF systems are costlier, their sustainability and efficiency make them a promising option for future water purification, especially under conditions that enhance their commercial viability.

Overall, Farshut WPP is more cost-effective than Nagaa Hamadi WPP in terms of salaries and wages by 64.8%, electricity usage by 82.3%, and land footprint by 73.5%. Conversely, Nagaa Hamadi WPP is more economical than Farshut WPP regarding chemicals usage by 25.6%, Capital Expenditures (CAPEX) by 17.5%, and Operating Expenditure (OPEX) by 89.6%.

Table 2. Main data about the two WPPs

P.O.C	Nagaa Hamadi WPP	Farshut WPP
Area (m^2)	42,000	15,000
Design capacity (m^3/day)	70,000	34,000
Water losses (m^3/day)	4,590	4,590
OPEX (E£ /year)	5,939,583	5,098,490
Energy consumed per year (KW/year)	10,998,400	4,427,488
Cost of energy per year (E£ /year)	13,205,385	5,277,842
Cost of all chemicals per year (E£ /year)	1,904,541	3,762,427
Source of water	River Nile	
Date of opening	1999	2019
Salaries per year (E£ /year)	3,873,498	1,219,700
Cost of consumed chlorine per year (E£ /year)	724,413	112,507
Cost of consumed Alum per year (E£ /year)	1,180,128	0.0
Cost of consumed CEB chemicals per year (E£ /year)	0.0	3,649,920

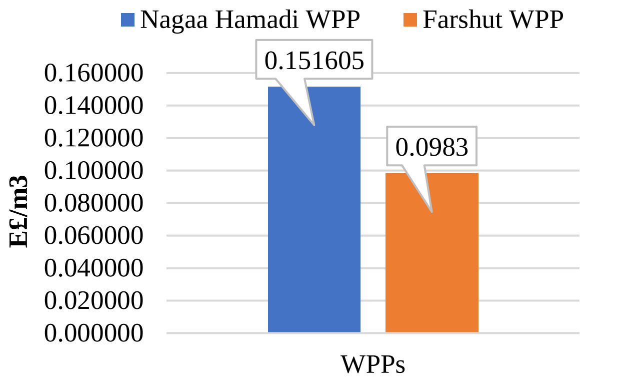

Fig. 1 Salaries and wages are given to produce (1) m3 of treated water

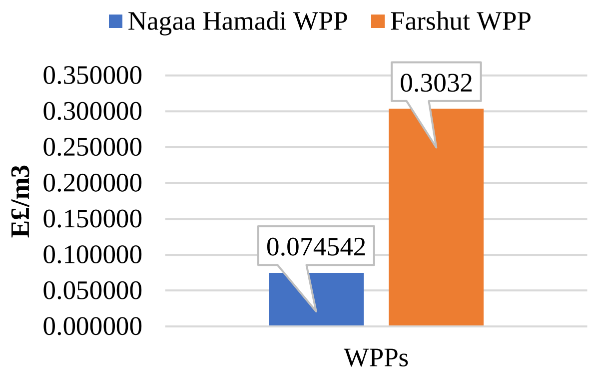

Fig. 2 Cost of chemicals consumed to produce (1) m3 of treated water

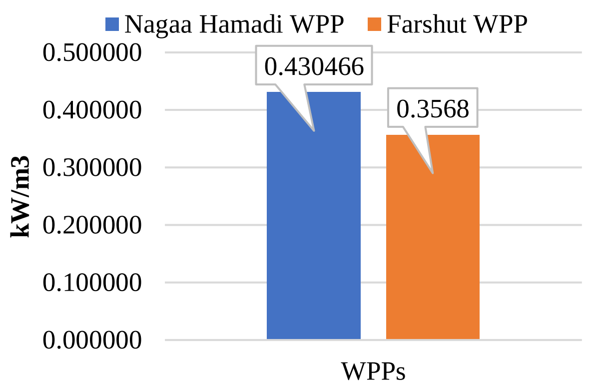

Fig. 3 Electricity consumption to produce (1) m3 of treated water

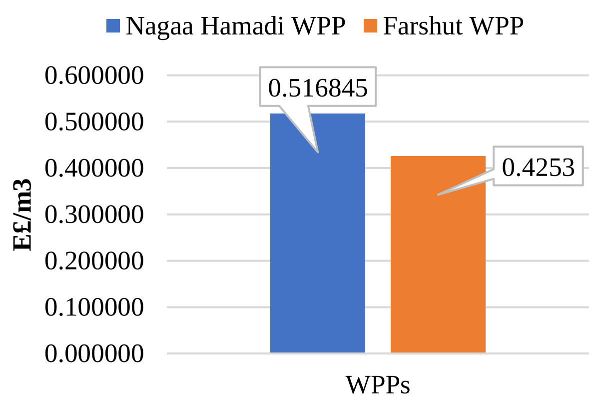

Fig. 4 Cost of electricity consumed to produce (1) m3 of treated water

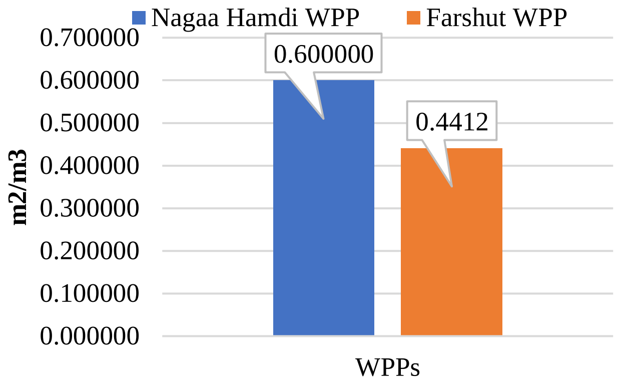

Fig. 5 Footprint area to produce (1) m3 of treated water

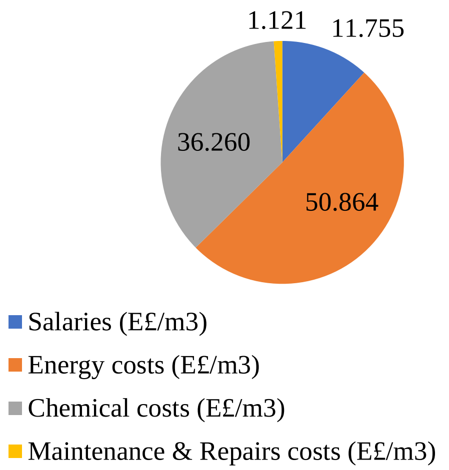

Fig. 6 OPEX divisions/components of Farshut WPP to produce (1) m3 of treated water

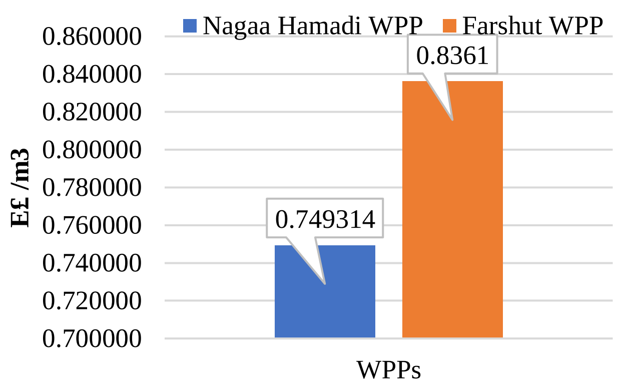

Fig. 7 OPEX to produce (1) m3 of treated water

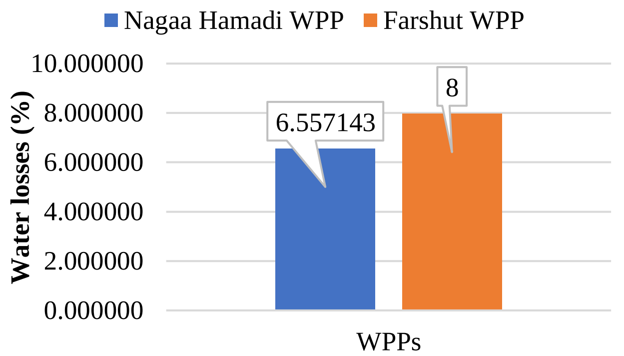

Fig. 8 Percentage of water losses

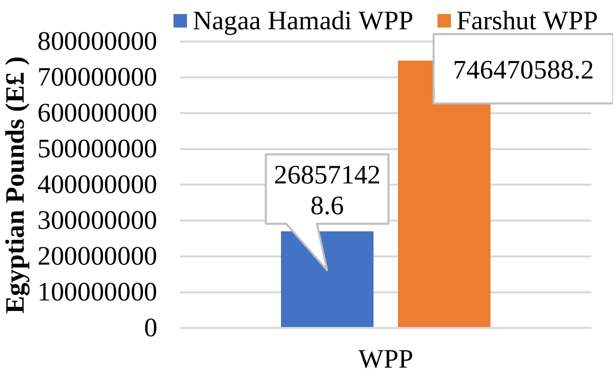

Fig. 9 Construction cost of the two WPPs in 2024

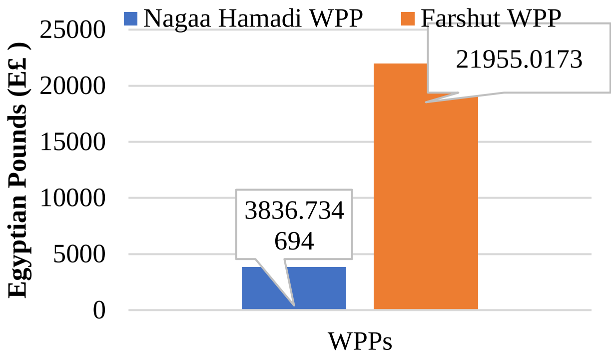

Fig. 11 CAPEX in 2024 to produce (1) m3 of treated water

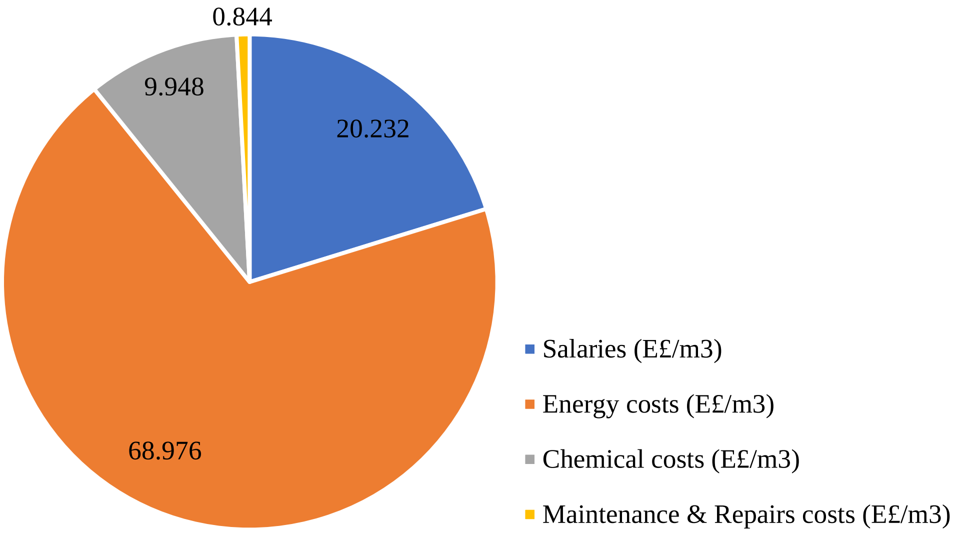

Fig. 10 OPEX divisions/components of nagaa hamadi WPP to produce (1) m3 of treated water

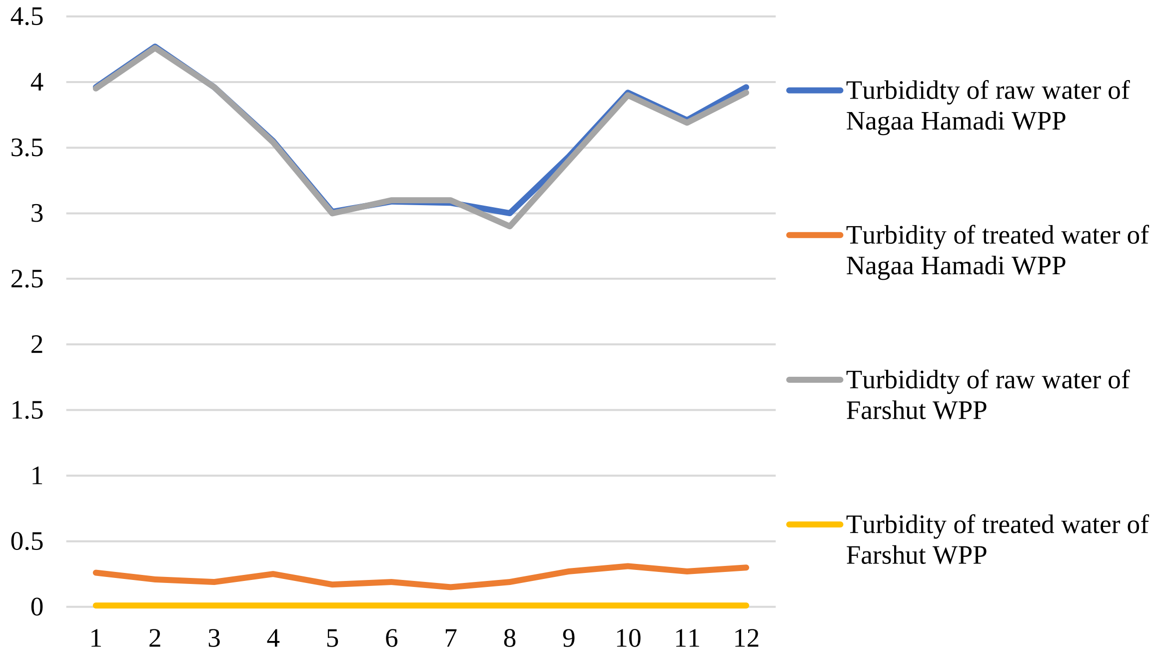

Fig. 12 Turbidity of raw water and treated water of nagaa hamadi WPP & Farshut WPP during 2023

Fig. 13 Nagaa hamadi WPP layout from Google Earth

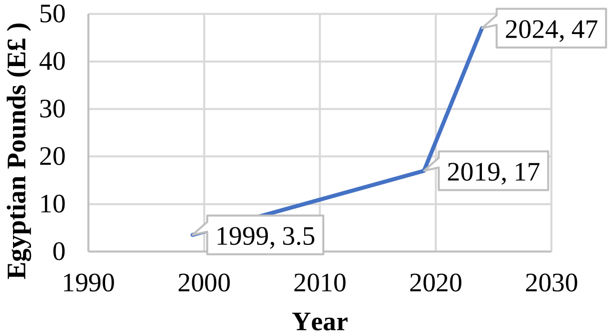

Fig. 14 1 USD to EGP respecting yearly inflation rate

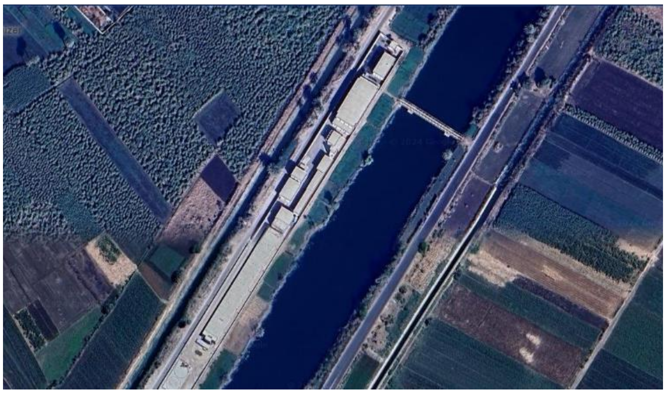

Fig. 15 Farshut WPP layout from Google Earth

Acknowledgements

The corresponding author sincerely thanks everyone who supported him during the research. He is especially thankful to the esteemed authors who supervised and helped him a lot during the research and for their invaluable guidance and encouragement, which significantly shaped his creative and critical thinking. He also deeply appreciates their extensive knowledge and technical assistance. His gratitude extends to the Holding Company for Water and Wastewater in Egypt (HCWW), along with the managers, engineers, and technicians at Farshut WPP and Nagaa Hamadi WPP, for their cooperation and support during the visits and research.

List of Abbreviations

UF	Ultrafiltration/Ultra-Filtration
WPP	Water Purification Plant
TMP	Transmembrane-Pressure
PVDF	Polyvinylidene Fluoride
NOM	Natural Organic Matter
NTU	Nephelometric Turbidity Unit
CIP	Cleaning In Place
CEB	Chemical Enhanced Backwash
USD($)	United States Dollar
EGP(E£)	Egyptian Pound
CAPEX	Capital Expenditure/Expenses
OPEX	Operating Expenditure/Expenses
HF	Hollow Fiber
EFM	Enhanced Flux Maintenance
ASRF	Air Scrubbing and Reverse Filtration
TSS	Total Suspended Solids
PES	Polyethersulfone
PSU	Polysulfone
PP	Polypropylene
PAN	Polyacrylonitrile
P.O.C	Point Of Comparison

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