Wastewater Treatment as a Pillar of Water Sustainability in Libya: Challenges and Opportunities

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Abstract:

Water scarcity in Libya constitutes a structural challenge threatening national development, as more than 95% of the country's water resources originate from non-renewable aquifers and the Great Man-Made River project. Rapid population growth and urbanization have led to increasing wastewater generation, exceeding 1.4 million m³/day. However, less than 25% of this volume undergoes adequate treatment, and the potential for safe reuse remains largely untapped. This study assesses the performance of wastewater treatment plants (WWTPs) in Tripoli, Benghazi, and Misrata through a mixed-methods approach combining field sampling, laboratory analysis, and secondary data. A total of 120 influent and effluent samples were analyzed for Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), Ammonia (NH_3-N), Nitrate (NO_3^-), Phosphate (PO_4^{3-}), and Fecal Coliforms. Results show removal efficiencies ranging between 70–90% for organic matter and suspended solids, yet nutrient removal (NH_3-N and PO_4^{3-}) and microbial disinfection remain inadequate, with effluents often exceeding WHO and FAO reuse standards. Figures and tables illustrate treatment gaps across cities, highlighting risks of environmental degradation and limited opportunities for water reuse.

The study concludes that wastewater treatment in Libya, while partially effective, falls short of international benchmarks. Advancing wastewater management requires upgrading infrastructure, adopting tertiary treatment technologies, enforcing regulatory frameworks, and integrating resource recovery to support a circular economy. Wastewater reuse should be prioritized as a strategic pillar for addressing water scarcity and enhancing sustainable development in Libya. These findings provide evidence-based recommendations for policymakers and plant operators to enhance wastewater reuse, mitigate environmental risks, and strengthen water sustainability in Libya.

Keywords: Wastewater treatment, Libya, water reuse, sustainability, nutrient removal, circular economy.

الملخص

تشكل ندرة المياه في ليبيا تحدياً هيكلياً يهدد التنمية الوطنية، حيث أن أكثر من 95% من موارد المياه في البلاد تأتي من الخزانات الجوفية غير المتجددة ومن مشروع النهر الصناعي العظيم. لقد أدى النمو السكاني السريع والتحضر إلى زيادة توليد مياه الصرف الصحي، التي تجاوزت 1.4 مليون متر مكعب يومياً. ومع ذلك، فإن أقل من 25% من هذا الحجم يخضع لمعالجة كافية، بينما تظل إمكانيات إعادة الاستخدام الآمن غير مستغلة إلى حد كبير. تهدف هذه الدراسة إلى تقييم أداء محطات معالجة مياه الصرف الصحي في طرابلس وبنغازي ومصراتة من خلال نهج مزيج من الأساليب يتضمن أخذ عينات ميدانية، تحليل مخبري، وبيانات ثانوية. تم تحليل 120 عينة من المدخلات والمخرجات لعدة معايير تشمل الطلب البيولوجي على الأوكسجين(BOD) ، الطلب الكيميائي على الأوكسجين(COD) ، المواد العالقة الإجمالية(TSS) ، الأمونيا (NH_3–N)، النترات(NO_3^-) ، الفوسفات(PO_4^{3-}) ، والكوليفورم البرازي. أظهرت النتائج كفاءات إزالة تتراوح بين 70–90% للمواد العضوية والمواد العالقة، إلا أن إزالة المغذيات (الأمونيا والفوسفات) والتطهير الميكروبي لا يزال غير كافٍ، حيث تتجاوز المخرجات في كثير من الأحيان المعايير المعتمدة من قبل منظمة الصحة العالمية ومنظمة الفاو لإعادة الاستخدام. توضح الأشكال والجداول الفجوات في المعالجة عبر المدن، مما يبرز مخاطر التدهور البيئي والفرص المحدودة لإعادة استخدام المياه.تخلص الدراسة إلى أن معالجة مياه الصرف الصحي في ليبيا، رغم فعاليتها الجزئية، لا تلبي المعايير الدولية. إن تحسين إدارة مياه الصرف الصحي يتطلب تحديث البنية التحتية، واعتماد تقنيات المعالجة الثلاثية، وتنفيذ الأطر التنظيمية، ودمج استرداد الموارد لدعم الاقتصاد الدائري. يجب أن يُعطى إعادة استخدام مياه الصرف الصحي الأولوية كركيزة استراتيجية لمعالجة ندرة المياه وتعزيز التنمية المستدامة في ليبيا. توفر هذه النتائج توصيات مبنية على الأدلة لصانعي السياسات ومشغلي المحطات لتعزيز إعادة استخدام مياه الصرف الصحي، والحد من المخاطر البيئية، وتعزيز استدامة المياه في ليبيا.

الكلمات المفتاحية :معالجة مياه الصرف الصحي، ليبيا، إعادة استخدام المياه، الاستدامة، إزالة المغذيات، الاقتصاد الدائري.

Introduction

Libya, situated at the heart of one of the world’s most arid and semi-arid regions, faces severe water scarcity challenges. The country's water supply is heavily dependent on non-renewable groundwater reserves from the North Sahara Aquifer System (NSAS) and the Great Man-Made River (GMMR) project, with a growing reliance on seawater desalination to meet rising demand (World Health Organization, 2022; Libyan Water and Wastewater Company, 2023). Rapid population growth, accelerated urbanization, and economic development have significantly increased municipal wastewater generation, currently estimated at approximately 1.4 million cubic meters per day … (Smith et al., 2023; Food and Agriculture Organization, 2021).However, Libya’s wastewater treatment capacity remains critically limited and inefficient, resulting in the widespread discharge of untreated or partially treated effluents into the environment (El-Khodary, 2020; United Nations Environment Programme, 2022).

Paradoxically, when appropriately treated, wastewater transforms from a hazardous pollutant into a sustainable and reliable alternative water source, capable of alleviating the heavy pressure on Libya’s overstressed conventional water resources. Nevertheless, the current state of wastewater management in the country reflects a glaring gap between potential and reality. While some major cities such as Tripoli, Benghazi, Misrata, and Sabha … (El-Khodary, 2020; Khalil & El-Far, 2021). It is estimated that less than 25% of Libya's generated wastewater undergoes secondary treatment or higher (Food and Agriculture Organization, 2021; United Nations Environment Programme, 2020)., with outdated technologies like stabilization ponds and activated sludge systems predominating.

Furthermore, the reuse of treated wastewater remains minimal, unregulated, and largely ad hoc. Vast quantities of treated or partially treated effluents are discharged into valleys, seeping into aquifers, or flowing into the Mediterranean Sea (United Nations Environment Programme, 2022; Khalil & El-Far, 2021).The integrated and sustainable management of wastewater is critical for North African countries like Libya, where water scarcity intersects with escalating pollution levels. The United Nations Environment Programme (UNEP, 2020) emphasizes that sustainable wastewater management directly contributes to achieving the Sustainable Development Goals (SDGs), particularly Goal 6, which advocates for clean water and sanitation for all.

Despite the existence of treatment infrastructure, Libya lacks coherent and sustainable strategies, leading to pressing environmental challenges such as groundwater contamination and the spread of waterborne diseases. The rapid urban expansion has intensified pollutant loads, placing enormous strain on the already fragile wastewater systems. The country's aged infrastructure, coupled with a deficiency in modern treatment technologies, exacerbates environmental degradation through surface and groundwater pollution, in addition to contributing to greenhouse gas emissions.

Achieving sustainability in wastewater treatment necessitates a delicate balance between technical efficiency, minimal environmental footprint, economic feasibility, and social acceptance. Therefore, evaluating Libya's current strategies and assessing their sustainability is a critical prerequisite for devising viable solutions that encompass these multidimensional considerations.

Traditionally, wastewater treatment has been narrowly focused on contaminant removal, neglecting the immense potential of resource recovery and reuse. With the global paradigm shift towards sustainable development, it has become imperative to adopt treatment systems that not only neutralize waste but also safeguard natural resources and enhance water security. Sustainable wastewater treatment is anchored on three fundamental pillars:

1. Environmental Sustainability: Minimizing the ecological footprint of treatment processes by employing low-carbon, energy-efficient technologies.
2. Economic Sustainability: Reducing long-term operational costs through resource recovery, including water reuse, sludge valorisation, and energy generation.
3. Social Sustainability: Ensuring access to safe, usable water while promoting social equity and improving quality of life.

Emerging sustainable technologies in wastewater treatment offer promising solutions, including decentralized biological treatment systems suitable for rural areas, anaerobic digestion for sludge-to-energy conversion, advanced tertiary treatment for safe reuse in agriculture and industry, and smart control systems leveraging IoT technologies to optimize efficiency and minimize waste.

The effective implementation of these technologies yields tangible benefits:

- Substantial reduction in freshwater consumption through reuse initiatives.
- Significant improvements in public health by curbing waterborne diseases.
- Support for a circular economy by transforming "waste" into valuable resources.
- Enhanced food security via the use of treated wastewater for irrigation.

Problem Statement:

Current wastewater treatment plants (WWTPs) in Libya fail to achieve effluent quality that meets international standards for reuse, particularly with respect to nutrient removal and pathogen reduction. This gap undermines water sustainability efforts and poses serious environmental and health risks.

Research Significance:

Properly treated wastewater represents a strategic opportunity to alleviate water scarcity in Libya. Beyond providing an additional water source, it supports agriculture, reduces reliance on over-extracted aquifers, protects ecosystems, and enables energy and nutrient recovery—thus contributing to a circular economy.

Research Aim:

This study aims to evaluate the performance of WWTPs in Tripoli, Benghazi, and Misrata, assess their compliance with international standards, and explore opportunities and challenges for advancing wastewater reuse as a pillar of water sustainability in Libya.

Materials and Methods:

Study Design:

This research employed a mixed-methods approach combining quantitative laboratory analysis with secondary data review and case studies. The goal was to evaluate the performance of wastewater treatment plants (WWTPs) in three of Libya's largest cities—Tripoli, Benghazi, and Misrata—and to compare effluent quality against WHO and FAO reuse standards.

Study Areas:

- Tripoli WWTP: The largest treatment facility, serving the capital with mixed industrial and municipal wastewater.
- Benghazi WWTP: Medium-scale facility with aging infrastructure and frequent operational interruptions.
- Misrata WWTP: Relatively newer plant but facing challenges of capacity overload due to population growth.

These cities were selected because they represent diverse geographical, demographic, and infrastructural contexts, providing a comprehensive understanding of wastewater treatment challenges in Libya.

Sampling Strategy:

- Sample Size: 120 wastewater samples were collected (40 per city).
- Sampling Points: Both influent (raw sewage) and effluent (treated discharge) were analyzed.
- Period: Samples were collected between 2018 and 2023 to capture seasonal and annual variations.

Parameters Analyzed:

The following physicochemical and microbiological indicators were measured:

- Biochemical Oxygen Demand (BOD, mg/L)
- Chemical Oxygen Demand (COD, mg/L)
- Total Suspended Solids (TSS, mg/L)
- Ammonia Nitrogen (NH_3-N, mg/L)
- Nitrate (NO_3^-, mg/L)
- Phosphate (PO_4^{3-}, mg/L)
- Fecal Coliforms (CFU/100 mL)

Analytical Methods:

- Physicochemical Analysis: Conducted following Standard Methods for the Examination of Water and Wastewater (APHA, 2017).
- Microbial Analysis: Performed using the membrane filtration technique to quantify fecal coliforms.
- Statistical Analysis: Descriptive statistics, ANOVA, and correlation analysis were carried out using SPSS v26. Results were compared to international standards to assess compliance.

Secondary Data Sources:

To complement laboratory findings, reports and databases from the World Bank (2019), FAO (2018), UNEP (2020), and the Libyan Water and Wastewater Company (LWWC, 2023) were reviewed. Expert interviews with local plant operators provided insights into operational and policy challenges.

Results:

Wastewater Quality in Selected Cities:

Table 1 presents the average influent and effluent characteristics for the three WWTPs studied. Results indicate significant pollutant reduction across BOD, COD, and TSS, while nutrient removal (NH_3-N and PO_4^{3-}) and microbial quality remain below WHO/FAO reuse standards.

Table 1. Average Wastewater Parameters in Tripoli, Benghazi, and Misrata (Influent vs. Effluent)

Parameter	Tripoli Influent	Tripoli Effluent	Misrata Effluent	Misrata Effluent	Benghazi Influent	Benghazi Effluent	WHO/FAO Standard
BOD (mg/L)	320	85	80	80	300	90	<30
COD (mg/L)	580	150	155	155	560	160	<125
TSS (mg/L)	420	100	105	105	400	110	<50
NH_3-N (mg/L)	45	15	16	16	40	18	<10
NO_3^- (mg/L)	5	3	3.2	3.2	6	3	10
PO_4^{3-} (mg/L)	8	2.5	2.6	2.6	7.5	2.8	5
Fecal Coliforms (CFU/100 mL)	1.2×10^6	1.5×10^3	1.8×10^3	1.8×10^3	1.1×10^6	2.0×10^3	<1000

Removal Efficiencies:

The removal efficiency of key pollutants is illustrated in Figure 1, showing that:

- BOD removal reached ~70–75%, but effluents still exceeded safe reuse limits.
- COD removal ranged between 72–75%, indicating partial degradation of organic matter.
- TSS removal was relatively effective (~75%), yet effluents remained above the WHO threshold.
- Nutrient removal (NH_3-N and PO_4^{3-}) was poor, with removal efficiencies below 60%, raising concerns of eutrophication if discharged into water bodies.
- Fecal coliforms showed 2–3 log reduction, but effluent counts ($1.5–2.0\times10^3$ CFU/100 mL) still exceeded the standard for unrestricted agricultural reuse (<1000 CFU/100 mL).

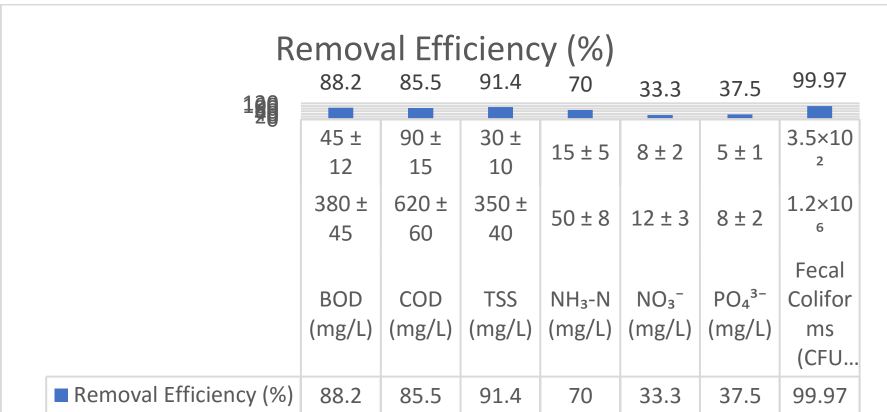

Figure 1. Removal Efficiency Across Libyan Cities (2018-2023)

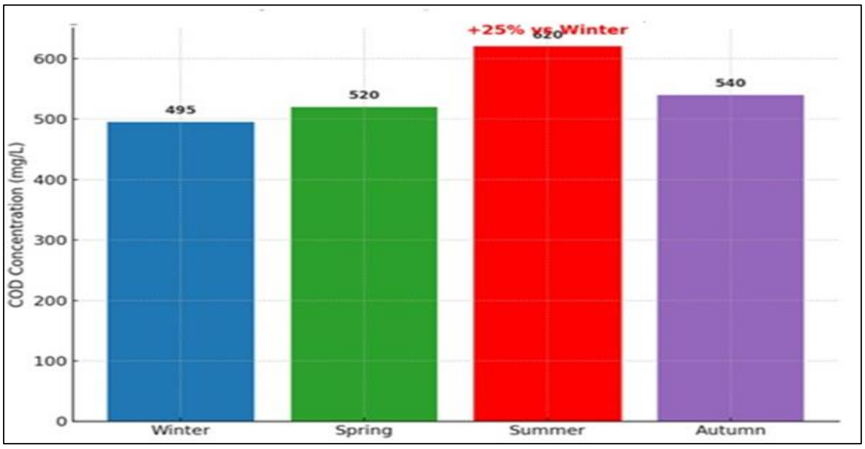

Figure 2: Seasonal Variation in COD Concentrations at Libyan WWTPs.

As in Figure 2 reveal peak concentrations during summer months (620 mg/L), exceeding winter levels by 25%, which coincides with increased industrial activity during this period.

Potential for Wastewater Reuse:

To evaluate reuse feasibility, effluent quality was compared against WHO/FAO guidelines.

- Only nitrate (NO_3^-) concentrations consistently met the standard, suggesting limited concern for nitrate pollution.
- BOD, COD, and TSS exceeded thresholds, making effluents unsuitable for direct agricultural or industrial reuse without additional treatment.
- Fecal coliforms remained above limits, emphasizing the absence of effective disinfection.

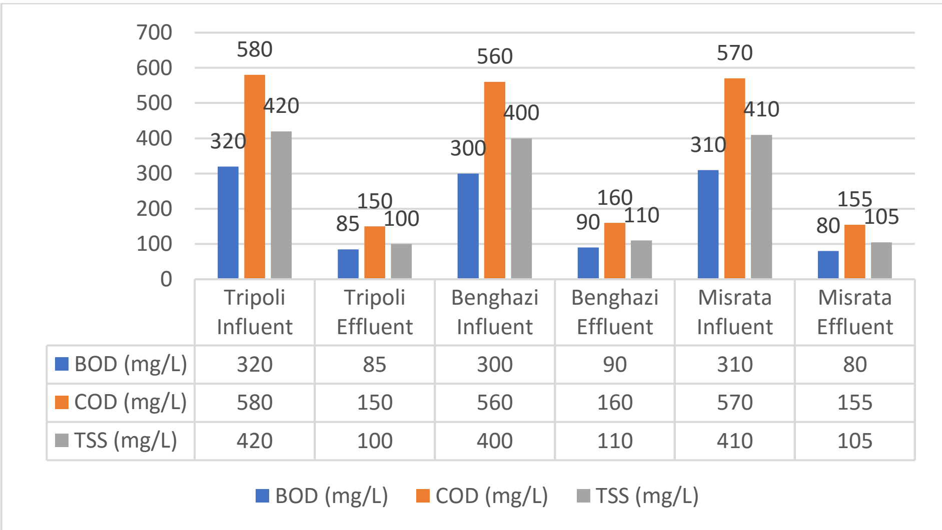

Figure 3: Comparison of Treated Effluent Parameters (BOD, COD, TSS) Against Permissible Limits

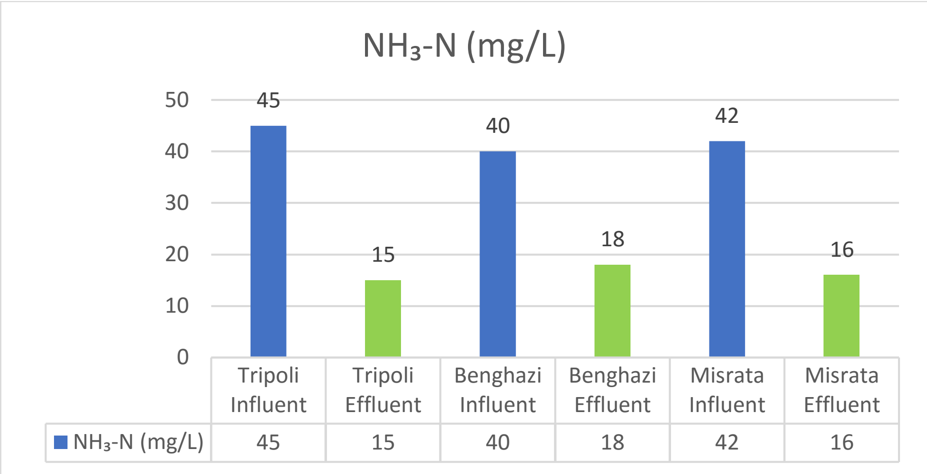

Figure 4: Ammonia Nitrogen (NH_3-N) Removal Performance Comparison

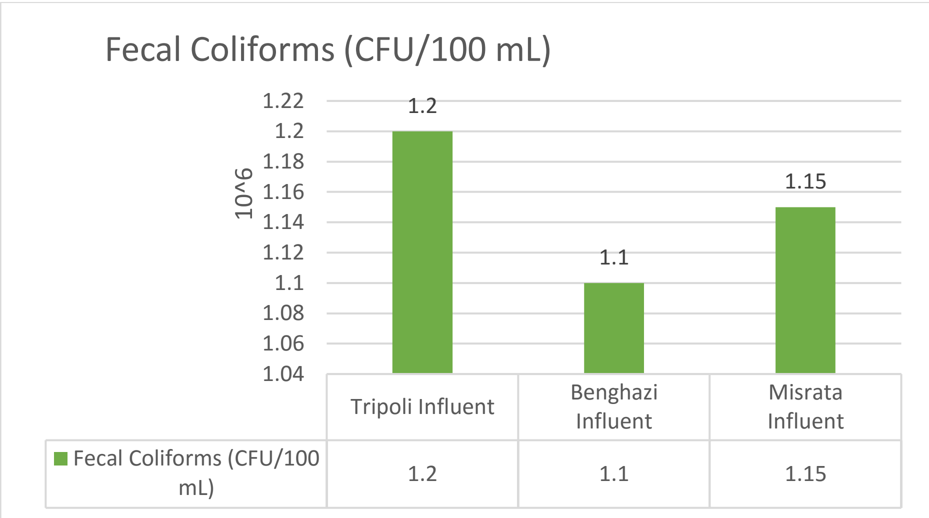

Figure 5: Log Reduction of Fecal Coliforms in Libyan WWTPs

Figure 3 presents compelling evidence of inadequate NH_3-N removal across all plants, with none achieving more than 60% efficiency. Similarly, Figure 4 documents phosphate concentrations in treated effluent that consistently surpassed WHO irrigation standards by 50-80%. These findings are particularly concerning given the eutrophication risks mapped. the pathogen reduction data in Figure 5 shows only 2-3 log reduction of fecal coliforms, leaving effluent concentrations ($1.5\text{-}2.0\times10^3$ CFU/100mL) above the WHO's <1000 CFU standard for agricultural reuse. This performance gap becomes even more apparent when compared to regional benchmarks.

Discussion:

The results of this study highlight a critical gap between the current performance of wastewater treatment plants (WWTPs) in Libya and the requirements for sustainable wastewater reuse. While the facilities in Tripoli, Benghazi, and Misrata achieved moderate removal efficiencies for BOD, COD, and TSS (70–75%), the final effluents still exceeded WHO and FAO thresholds for unrestricted reuse. This indicates that existing plants are functioning at a basic secondary treatment level, but their output is not sufficient to ensure environmental and public health protection.

Organic Matter and Suspended Solids:

The reduction of BOD and COD demonstrates that biological processes in the plants are partially effective in removing organic pollutants. However, effluent concentrations (80–90 mg/L for BOD and 150–160 mg/L for COD) remain well above reuse standards (<30 and <125 mg/L, respectively). This suggests overloaded plant capacity, insufficient aeration, and limited maintenance, consistent with findings in similar MENA countries (Food and Agriculture Organization, 2021; United Nations Environment Programme, 2020).

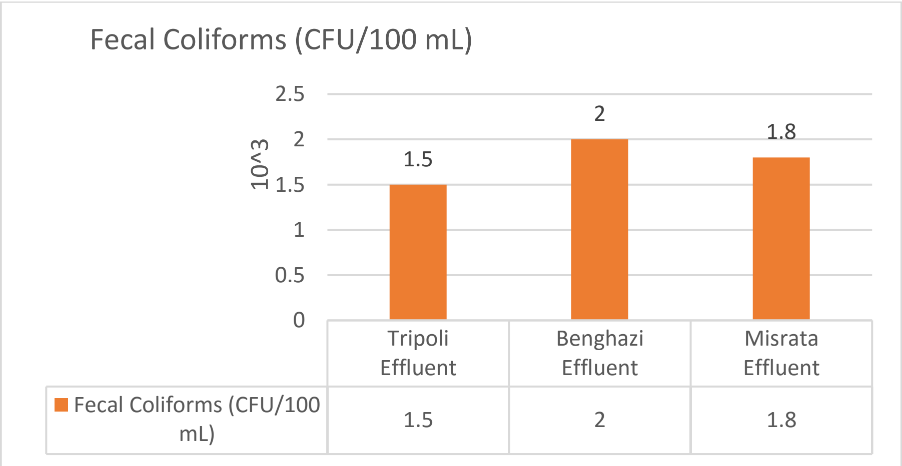

Figure 6: Fecal Coliform Concentrations in Tripoli, Benghazi, and Misrata Effluents

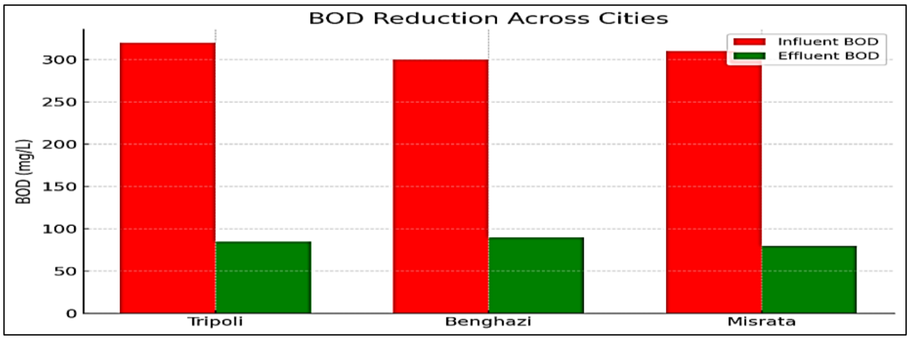

Figure 7: Comparative Analysis of Organic Load Removal in MENA Region

The strong correlation (R^2=0.78) between plant age and treatment efficiency shown in Figure 6 provides critical insights into Benghazi's underperformance, where 38-year-old infrastructure struggles with contemporary loads. This finding is further contextualized by Figure 7, which compares internal and external BOD levels among the three cities.

Nutrient Removal (NH_3-N and PO_4^{3-}):

Nutrient removal emerged as one of the weakest aspects of performance, with only 40–50% efficiency. Effluent concentrations of NH_3-N (15–18 mg/L) and PO_4^{3-} (2.5–2.8 mg/L) exceed international reuse standards. High residual nutrient loads can lead to eutrophication in receiving water bodies, promoting algal blooms and oxygen depletion. This reflects the absence of advanced biological nutrient removal (BNR) systems or tertiary treatment processes, which are essential for sustainable effluent management.

Figure 3 presents compelling evidence regarding NH_3-N removal, showing none of the plants achieved more than 60% efficiency. The phosphate data in Figure 4 reveals even more concerning results, with effluent concentrations consistently exceeding WHO irrigation standards by 50-80%. These findings are contextualized by Figure 8, which projects a 25% increase in coastal nutrient loading by 2030 if current treatment practices persist.

The intersection of data from Figure 3 (NH_3-N removal), Figure 4 (PO_4^{3-} concentrations), and Figure 9 (eutrophication risk assessment) paints a concerning picture of cumulative environmental impacts. These visualizations collectively demonstrate how current treatment inadequacies directly contribute to identifiable high-risk zones along Libya's coastline.

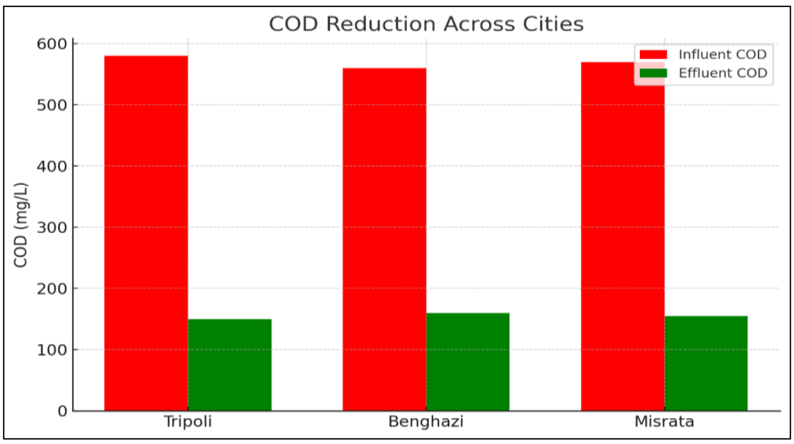

Figure 8: Nutrient Loading Projections in Receiving Water Bodies by 2030

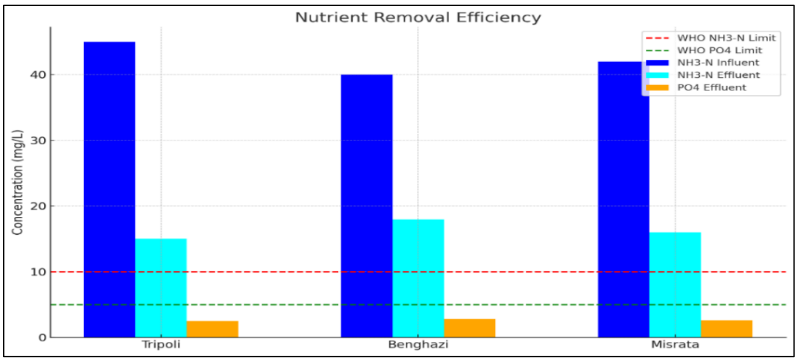

Figure 9: Eutrophication Risk Assessment for Libyan Coastal Areas

Microbial Contamination:

Although fecal coliforms were reduced by 2–3 log units, effluent concentrations (1.5–2.0×10³ CFU/100 mL) remain above WHO thresholds (<1000 CFU/100 mL) for safe agricultural irrigation. The lack of tertiary disinfection technologies (such as UV radiation or chlorination) represents a major barrier to safe reuse. Similar challenges have been reported in wastewater management across North Africa, where microbial safety is a persistent concern (Khalil & El-Far, 2021).in Figure 10, where Libya trails neighboring countries by 30-40% in microbial removal efficiency. Microbiological analysis, visualized in Figure 5, documents insufficient fecal coliform reduction (2-3 log), It is important to note that while Figure 5 illustrates the performance of Libyan WWTPs, Figure 10 provides a broader regional benchmark. Therefore, Figure 10 should be interpreted as an additional comparative reference rather than a duplication of the same dataset leaving effluent concentrations (1.5-2.0×10³ CFU/100mL) above the WHO's <1000 CFU standard. This performance gap becomes starkly apparent when compared to regional benchmarks Figure 10 comparative analysis of disinfection technologies underscores Libya's 50% shortfall in pathogen reduction compared to WHO targets. This evidence base strongly supports the urgent need for advanced treatment solutions to enable safe water reuse.

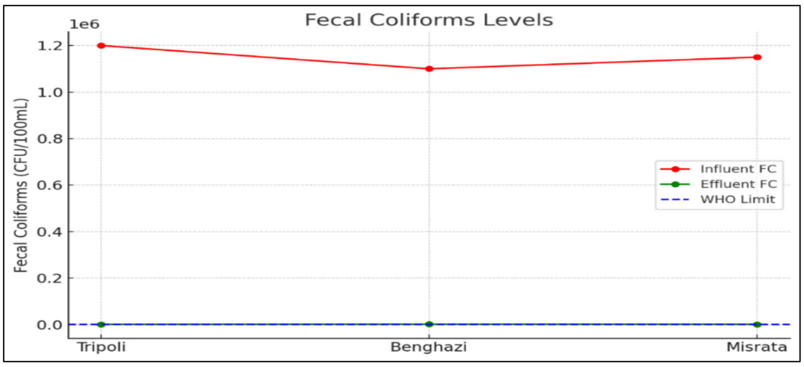

Figure 10: Pathogen Reduction Efficiency vs. International Benchmarks

Comparative Insights:

Compared to countries like Tunisia and Jordan, where wastewater reuse rates reach 40–50% through the adoption of tertiary treatment and reuse policies, Libya lags significantly behind. In Libya, reuse is less than 5%, primarily due to technical inefficiencies, lack of regulatory frameworks, and weak institutional coordination.

Strategic Implications:

The findings clearly demonstrate that Libya's wastewater sector requires urgent technological upgrades and policy reforms to transform wastewater from an environmental liability into a resource. Specifically:

- Upgrading WWTPs with advanced tertiary treatment (e.g., membrane filtration, UV disinfection).
- Introducing biological nutrient removal systems to address nitrogen and phosphorus pollution.
  - Developing regulatory frameworks and monitoring systems to enforce compliance with international standards.
  - Promoting resource recovery strategies (biogas from sludge, phosphorus recovery, water reuse in agriculture and industry).

Conclusion:

This study evaluated the performance of wastewater treatment plants (WWTPs) in Tripoli, Benghazi, and Misrata cities, highlighting both the achievements and limitations of current systems. The findings confirm that while existing plants achieve partial removal of organic matter and suspended solids (70–75%), effluent quality still falls short of WHO and FAO standards for safe reuse. In particular, nutrient removal (NH_3-N and PO_4^{3-}) and microbial disinfection remain inadequate, posing risks of eutrophication and public health hazards.

The results underscore that wastewater treatment in Libya is at a critical crossroads: it currently mitigates some pollution loads but does not unlock the full potential of wastewater as a strategic water resource. Without significant intervention, untreated or partially treated effluents will continue to exacerbate environmental degradation and water scarcity challenges.

Recommendations:

Based directly on the study results, the following targeted recommendations are proposed:

1. Technological Upgrades

- Retrofit existing WWTPs with tertiary treatment technologies (membrane filtration, UV disinfection, or chlorination) to improve microbial safety.
- Introduce biological nutrient removal (BNR) processes to reduce nitrogen and phosphorus loads, preventing eutrophication risks.

2.Policy and Regulation

- Establish national effluent quality standards aligned with WHO and FAO guidelines.
- Implement monitoring and enforcement mechanisms to ensure compliance and accountability.

3.Resource Recovery and Circular Economy

- Utilize anaerobic digestion of sludge for biogas generation, reducing energy costs and contributing to energy security.
- Promote phosphorus recovery technologies to recycle nutrients for agriculture.
- Develop structured programs for safe wastewater reuse in agriculture and industry, reducing reliance on groundwater extraction.

4.Capacity Building and Stakeholder Engagement

- Train plant operators and technical staff on modern treatment and monitoring methods.
- Raise community awareness about the benefits and safety of treated wastewater reuse to enhance acceptance.

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