Zero Liquid Discharge (ZLD) and Sludge Valorization: Dual Pathways for Sustainable Wastewater Management in India

Abstract

India's rapid industrial growth has intensified wastewater challenges, with Zero Liquid Discharge (ZLD) systems emerging as a regulatory solution. While ZLD enables partial water recovery, operator insights reveal persistent inefficiencies: 30–50% of wastewater remains unrecycled, often disposed of through unsustainable tanker discharge. High energy costs, heavy chemical use, and frequent breakdowns further undermine its viability, positioning ZLD more as a compliance tool than a sustainable practice. To address these gaps, this study explores sludge valorization as a complementary pathway. Textile effluent treatment plant sludge, after composting, demonstrated significant agronomic potential; enhancing germination, biomass, and yield across diverse crops by 13–40% compared to commercial NPK fertilizers. Laboratory analysis confirmed that heavy metals remained below FAO/WHO safety thresholds, ensuring crop and soil safety. This makes sludge-derived fertilizers safe and viable for farmer use, reducing reliance on costly chemicals. Together, the findings underscore the promise of hybrid models that integrate sludge valorization, innovation, and policy reform for sustainable wastewater management in India.

CHAPTER 1: INTRODUCTION

Bioremediation refers to the utilization of living organisms (like bacteria, fungi) to completely eliminate or reduce the concentration of deadly pollutants from the waste-water generated by industries after use. Basically, it is like employing nature's own organically cleaning organisms to get rid of pollution. In our case, this cleaning crew is made up of various minute living beings called microorganisms (like bacteria and fungi). These microorganisms eat up harmful substances in wastewater and turn them into less harmful or even harmless substances. There are different types of microorganisms that can be used, each good at breaking down different kinds of pollutants. For example, the Hydrocarbon degrading bacteria like Alcanivorax borkumensis, a.k.a Alca are really good at eating up oil spills, while others like Klebsiella and Enterobacter are the best potential organisms for bioremediation and bacteria-assisted phytoremediation strategies in soils contaminated with heavy metals like arsenic, cadmium, and lead.

(Image 1; Reverse Osmosis Plant)

India's rapid industrialization has led to a significant increase in wastewater generation across various sectors such as textiles, chemicals, pharmaceuticals, tanneries, thermal power plants, and food processing industries. Industrial processes generate wastewater rich in pollutants, including heavy metals, organic contaminants, suspended solids, and toxic chemicals. According to the Central Pollution Control Board (CPCB), Indian industries generate around 12,000 million liters per day (MLD) of wastewater, with many industrial hubs contributing disproportionately to this pollution load. Industrial areas such as Tirupur & Haryana (textile industry), Vapi (chemical industry), and Kanpur (leather tanneries) have been identified as critical zones where untreated or partially treated effluents have severely polluted rivers and groundwater sources. This unchecked discharge of industrial effluents has contributed to the degradation of ecosystems, contamination of agricultural land, and severe public health impacts in surrounding communities. As one study highlights, *"Zero Liquid Discharge is a wastewater treatment process developed to completely eliminate all liquid discharge from a system."* (Raja Sankar & Rajesh, 2017), emphasizing the need for such solutions in pollution-intensive industrial zones.

They work in various ways, like breaking down pollutants with special chemicals they produce (called enzymes) or by trapping pollutants by sticking them to their bodies. There are 2 major types of bioremediation as:- (i) in-situ bioremediation & (ii) ex-situ bioremediation. In-situ bioremediation refers to the treatment of contaminated waste-water without excavating or removing it from its place of origin and directly treating it through biological processes whereas Ex-situ bioremediation refers to the treatment of the contaminated substance with biological processes after it is removed from its origin and contained in a large vessel or tank.

[Image 2: Sand Media Filter and Carbon Filter Plant (UF → Media Filter → RO)]

India is one of the most water-stressed countries globally, with 18% of the world's population relying on just 4% of the global freshwater supply. The uneven spatial distribution of water, combined with high population density, has placed immense pressure on available water resources. Industrial zones located in water-scarce states such as Rajasthan, Gujarat, Tamil Nadu, and Maharashtra further exacerbate this challenge. In these regions, industries compete with agriculture and domestic users for increasingly scarce water resources. Groundwater levels in several industrial belts have declined to alarming levels due to over-extraction, while surface water bodies have been polluted by untreated industrial effluents. Sustainable water management, including water recycling, reuse, and efficient wastewater treatment, has become essential to ensure the long-term availability of water resources and to maintain ecological balance. Moreover, sustainable water management practices align with global sustainability goals and enhance the long-term operational viability of industries. As noted in *"Strategy of Zero Liquid Discharge to Mitigate Water Pollution: Indian Scenario,"* the adoption of innovative ZLD technologies ensures that wastewater is saved and recycled at supply resources, thereby alleviating water stress in heavily industrialized regions.

(Image 3; Water Flow Meters)

Zero Liquid Discharge (ZLD) is a method used by industries to make sure that no liquid waste is released into the environment. This is important because it helps protect the water sources. ZLD systems work by removing water from the waste, leaving only dry solid waste behind. The clean water can then be reused in the industry, which helps ensure water conservation. There are different technologies used in ZLD systems, like evaporation (where water is turned into steam and collected as clean water), crystallization (where dissolved substances are turned into solids and separated from water), and reverse osmosis (where water is pushed through a special filter that removes impurities). While ZLD systems are great for the environment, they can be expensive to set up and run. However, the long-term benefits, like saving water and reducing pollution, often outweigh the costs.

Zero Liquid Discharge (ZLD) is an advanced wastewater treatment process designed to eliminate liquid effluent discharge from industrial facilities. The concept of ZLD emerged from the need to achieve complete water recycling and resource recovery, particularly in areas where regulatory pressures and water scarcity necessitate stricter controls over industrial effluent discharge. ZLD systems aim to recover as much water as possible from industrial effluent streams, leaving behind only solid waste residues. Over the years, ZLD technologies have evolved significantly, incorporating multi-effect evaporators (MEE), reverse osmosis (RO), thermal crystallizers, and advanced filtration systems. Hybrid ZLD systems combine membrane filtration and thermal evaporation technologies to maximize water recovery while minimizing energy consumption. As highlighted in the research paper *"The Global Rise of Zero Liquid Discharge for Wastewater Management," "Three membrane-based processes—ED, FO, and MD—emerge as alternative ZLD technologies to brine concentrators to further concentrate the wastewater after the RO stage."* This diversification of technologies allows industries to select the most cost-effective and energy-efficient solutions based on the composition of their wastewater.

Sustainable management of industrial wastewater means finding ways to treat and reuse wastewater so that it doesn't harm the environment. By using bioremediation and ZLD systems together, industries can clean their wastewater more effectively and ensure that they aren't releasing harmful substances into the environment. This approach not only helps protect our planet but also supports industries in following environmental rules and using resources more wisely.

(Image 4; Physico-Chemical Reaction Chamber with Ferrous, Lime, and Polyelectrolyte Dosing, followed by Sludge Settler)

Recognizing the urgent need to control industrial water pollution, regulatory bodies like the Central Pollution Control Board (CPCB) have introduced stringent discharge norms and mandated ZLD implementation for specific high-polluting sectors. The textile industry, particularly dyeing units in Tamil Nadu's Tirupur cluster and textile industry in Haryana's Panipat, were among the first sectors mandated to adopt ZLD due to severe pollution of local rivers and groundwater. Similarly, leather tanneries in Kanpur and Unnao, which release chromium-laden effluents, have been directed to implement ZLD systems. Pharmaceutical and chemical industries, which generate toxic and non-biodegradable effluents, are also subject to strict ZLD requirements in industrial hotspots such as Ankleshwar and Vapi. The thermal power sector, responsible for large-scale water consumption and effluent generation, has also been brought under stricter water use and discharge norms, with many plants adopting ZLD for ash pond effluents and cooling tower blowdowns. As documented in *"Zero Liquid Discharge (ZLD) Industrial Wastewater Treatment Systems as Sustainable Development Basic Ecological Components,"* the implementation of ZLD at industrial sites like the Verkh-Isetsky steelworks showcases how environmental responsibility and operational efficiency can co-exist, even in heavy industries.

The adoption of ZLD aligns closely with the principles of circular economy, where waste streams are minimized, and resources are continuously recovered and reused within industrial processes. By implementing ZLD, industries can recycle water for process use, recover valuable salts or by-products, and reduce dependency on freshwater sources. This shift from a linear "use-and-dispose" model to a circular "treat-recycle-reuse" approach supports not only environmental protection but also economic efficiency, especially in water-scarce areas where water procurement and wastewater treatment costs are significant. As described in *"Innovations in Textile Wastewater Management: A Review of Zero Liquid Discharge (ZLD) Systems and Future Outlook," "Zero liquid discharge (ZLD) technology emerges as a transformative solution for sustainable wastewater management in the textile industry, emphasizing water recycling and discharge minimization."* Moreover, ZLD contributes to corporate sustainability goals, enabling industries to demonstrate compliance with environmental norms, enhance brand reputation, and gain competitive advantages in global markets that increasingly value sustainable production practices. In the long run, integrating ZLD into broader sustainability strategies helps industries contribute to UN Sustainable Development Goals (SDG 6 - Clean Water and Sanitation, and SDG 12 - Responsible

Consumption and Production), fostering a more resilient and resource-efficient industrial sector.

[Image 5; Water Softer Plan (Magnesium & Calcium Removal)]

1) Early Methods of Wastewater Management-

Ancient Civilizations (10,000 BC – 400 AD)

The earliest known urban centers in Mesopotamia had rudimentary drainage systems that diverted wastewater away from populated areas. These systems, though basic, showcased early attempts to manage waste, yet the Mesopotamians lacked an understanding of pollution, leading to the unintentional contamination of nearby rivers and water bodies. Their disposal methods reflected a survivalist mentality, with little consideration of the long-term environmental impact. Also, in Harappa and Mohenjo-Daro, advanced drainage systems, such as brick-lined drains, carried wastewater away from homes and public baths. This civilization displayed a surprisingly early understanding of sanitation and public health, making their practices a standout in ancient wastewater management. These early systems, although revolutionary for their time, still lacked a scientific understanding of pollution and its consequences on surrounding ecosystems.

The Egyptians implemented various systems to handle wastewater, including channels and rudimentary filtration systems. These methods were primarily used for irrigation, but the untreated wastewater often contaminated nearby rivers, particularly the Nile. While being innovative in terms of irrigation, the Egyptians still faced numerous challenges regarding the treatment and environmental management of sewage. Even the Romans developed one of the most advanced sewer systems of the ancient world, most notably the **Cloaca Maxima**, which carried sewage through pipes into the Tiber River. This system, though highly efficient for moving waste away from the city, contributed significantly to pollution and public health risks. The Romans, much like their predecessors, lacked the knowledge of how untreated wastewater affected public health and ecosystems, often creating problems downstream. Despite their engineering prowess, their methods represented a trade-off between immediate urban cleanliness and long-term environmental damage.

Medieval Period Management Strategies (400 AD – 1600 AD)

Following the collapse of the Roman Empire, urban sanitation efforts regressed considerably. Waste was often dumped into open gutters, which floodwaters would flush into nearby rivers. This rudimentary disposal method worsened as medieval cities grew, leading to contaminated water supplies and widespread disease outbreaks. The lack of centralized systems and political instability during this period hindered any progress in wastewater management.
Poor waste management contributed to the spread of the **Black Death**, which decimated Europe in the 14th century. Dense populations, combined with the absence of proper waste disposal systems, allowed vermin to thrive in the filth, further accelerating the spread of diseases. This era marked a period where the consequences of poor sanitation became brutally apparent, but knowledge of microbiology was still primitive. In response to England's unsanitary conditions, England’s King Edward III mandated the employment of “Rakers” to remove refuse from the streets and gutters, which then was dumped into rivers like the Thames, contributing to pollution and waterborne diseases. This was one of the first attempts at organized waste removal, although the environmental awareness necessary to treat wastewater was still absent.

By the mid-19th century, London’s **Thames River** had become so polluted from untreated sewage that the unbearable stench prompted political and social reforms. Known as "The Great Stink," this event pushed the government to build modern sewage systems, significantly improving urban sanitation. Other than that, across Europe and the United

States, repeated cholera outbreaks were tied to the discharge of untreated wastewater into public water supplies. The link between contaminated water and disease transmission spurred public health campaigns and motivated cities to develop wastewater treatment systems. Developing germ theory and increasing scientific understanding of waterborne diseases were crucial in shaping modern approaches to wastewater management.

Cities like Paris, London, and New York began constructing comprehensive sewage systems in response to health crises and growing urban populations. The construction of these systems, combined with stricter regulations, marked the beginning of organized, modern sanitation efforts. In the early 1900s, many cities introduced organized waste collection services. The development of sanitary landfills and incineration facilities replaced earlier methods like open dumping. These advances were driven by increasing awareness of environmental sustainability and the growing demand for clean, safe urban spaces. Public health improvements, combined with technological advances, enabled more efficient and environmentally friendly waste management practices.

By the mid-20th century, innovations like wastewater treatment plants, biological filtration, and sludge treatment revolutionized waste management. Environmental regulations such as the **Clean Air Act (1970)** and **Clean Water Act (1972)** in the United States introduced stricter controls on pollutants. These advances not only improved water and air quality but also laid the groundwork for modern approaches like bioremediation and **Zero Liquid Discharge (ZLD)** systems.

1.2 Industrial Revolution and the Need for Sustainable Solutions:-

The Industrial Revolution, beginning in the mid-18th century, marked a significant shift in global production and urbanization and thus transformed economies through mechanized production and rapid industrialization. However, this period also introduced significant environmental challenges, particularly with wastewater management. As industrialization intensified and cities grew around the increasing number of mills and factories, many streams and rivers also became open sewers. Manufacturers dumped millions of gallons of waste into waterways where it mixed with copious amounts of raw municipal sewage, industrial waste, heavy oils and chemicals greatly worsening the frequency and severity of disease epidemics.

As early as the late 19th century, signs of severe water quality issues began to emerge, with bodies of water becoming breeding grounds for diseases. Improper waste disposal severely affected aquatic ecosystems, resulting in the loss of wildlife.

The environmental impacts of industrialization gained widespread recognition in the 20th century. Rachel Carson's ground-breaking book *Silent Spring* (1962) catalyzed a global movement that drew attention to the ecological damage caused by industrial pollutants. This shift in consciousness spurred the development of stricter environmental regulations and innovative solutions aimed at reducing industrial waste. Key among these were the introduction of recycling programs, sustainable manufacturing practices, and Zero Liquid Discharge (ZLD) systems, which minimized wastewater output and promoted water reuse.

One of the most alarming examples of industrial pollution during the mid-20th century was the repeated fires on the Cuyahoga River in Ohio, which was so polluted with industrial wastes, oily debris & sewage that it famously caught fire several times, most notably in 1969. This event became a symbol of environmental neglect and led to the enactment of the National Environmental Policy Act (1970), a key legislative step toward regulating industrial emissions and protecting water resources.

The Cuyahoga River Fire, alongside other environmental disasters, pushed governments and citizens to demand action. In response, the U.S. Congress passed the National Environmental Policy Act (NEPA) in 1970, which was a landmark moment in the establishment of environmental regulations, leading to the creation of the Environmental Protection Agency (EPA), tasked with regulating industrial emissions and monitoring environmental risks.

As public awareness grew, events such as Earth Day in 1970 and its resurgence in 1990 mobilized millions globally to advocate for environmental health. The environmental movement catalyzed the development of sustainable practices, including stricter regulations on water pollution and the introduction of recycling programs. imperative.

The realization that industrialization had long-lasting environmental consequences led to innovations aimed at sustainable management. Technologies such as wastewater treatment plants, biological filtration, and Zero Liquid Discharge (ZLD) systems were developed to minimize industrial pollutants. These advancements represent critical steps toward ensuring that industrial activities do not come at the expense of environmental and public health.

[Image 6; Filter Press (Sludge Water Extraction)]

CHAPTER 2: METHOD

2.1 Rationale and Context

The management of sludge generated from textile effluent treatment plants (ETPs) poses a critical environmental and economic challenge in India. Despite Zero Liquid Discharge (ZLD) mandates, industries often struggle with high capital costs, intensive chemical requirements, and residual sludge disposal, which typically ends up incinerated or landfilled. This study was designed to address both operational and environmental gaps by:

1. Examining real-world ZLD system performance through operator interviews and site observations.
2. Transforming ETP sludge into a safe, nutrient-rich biofertilizer to evaluate its potential as a sustainable alternative to commercial NPK fertilizers.

This dual approach allows integration of industrial realities with experimental validation of sludge reuse under agricultural conditions.

2.2 Participants and Industry Insights

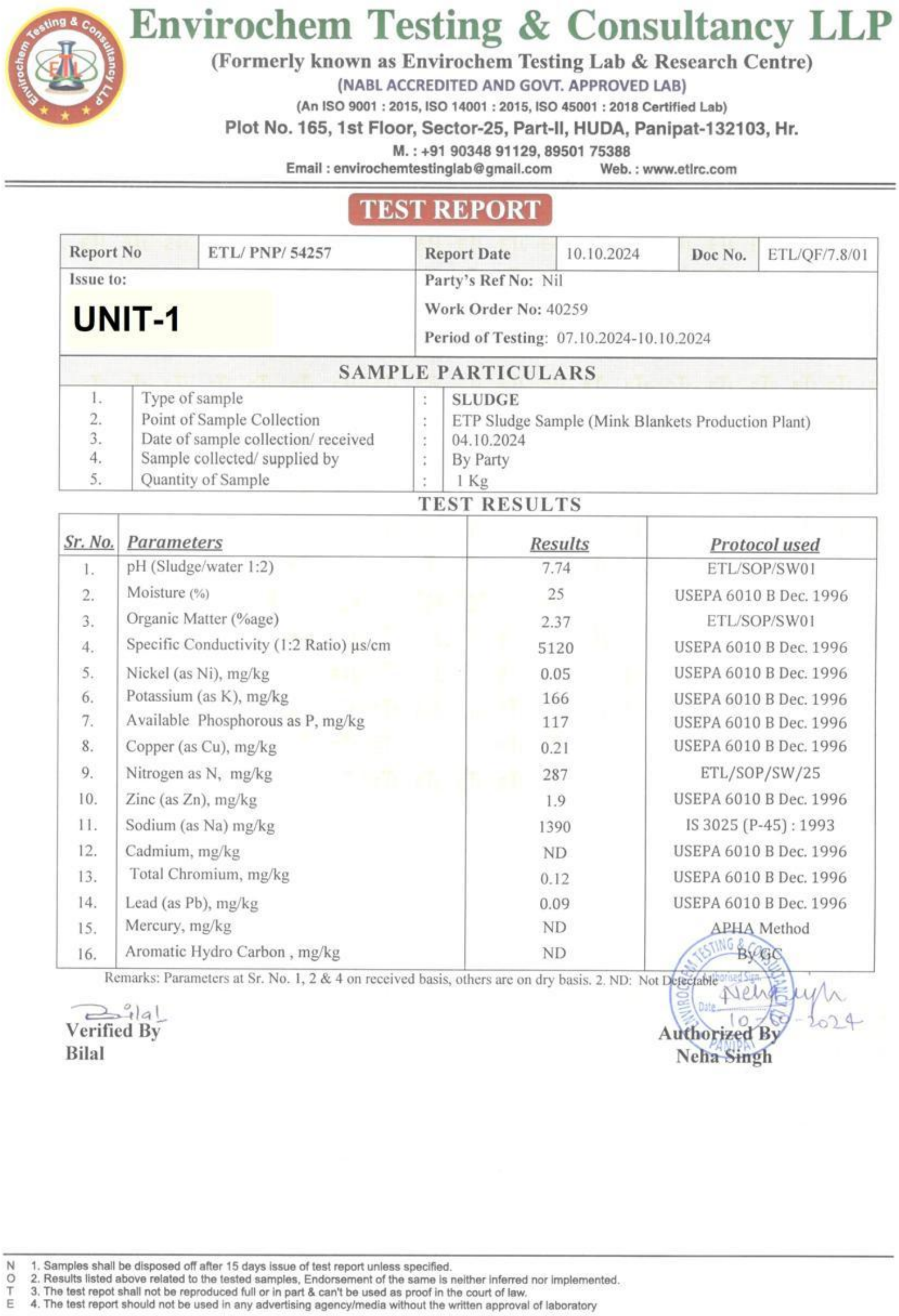
Four operators from different industrial facilities participated in this study. Their experience ranged from 6 to over 10 years, covering both biological ZLD systems (commonly used in textile and chemical industries) and a non-biological evaporator-based system. Industry visits were conducted to observe layouts, recycling efficiency, reject-water handling, and compliance practices. Semi-structured interviews captured perspectives on chemical use, system breakdowns, maintenance challenges, and the sustainability of ZLD. Responses were recorded, transcribed, and analyzed for recurring themes, providing a cross-sectional view of ZLD implementation in India.

2.3 Sludge Collection and Laboratory Analysis

Sludge samples were collected from two textile facilities in Panipat, Haryana. Laboratory analysis confirmed suitability for agricultural application, with key parameters as follows:

- **Unit 1:** pH 7.74, moisture 25%, organic matter 26%, potassium ~580 mg/kg, phosphorus ~470 mg/kg, sodium ~295 mg/kg.
- **Unit 2:** pH 9.28, moisture 39.4%, organic matter 28%, potassium ~600 mg/kg, phosphorus ~490 mg/kg, sodium ~310 mg/kg.

Trace metals (Ni, Zn, Cu, Pb, Cr) were present at sub-phytotoxic levels, while cadmium and mercury were absent.



Envirochem Testing & Consultancy LLP

(Formerly known as Envirochem Testing Lab & Research Centre)

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TEST REPORT

Report No	ETL/ PNP/ 54257	Report Date	10.10.2024	Doc No.	ETL/QF/7.8/01

Issue to: **UNIT-1**

Party's Ref No: Nil

Work Order No: 40259

Period of Testing: 07.10.2024-10.10.2024

SAMPLE PARTICULARS

1.	Type of sample	:	SLUDGE
2.	Point of Sample Collection	:	ETP Sludge Sample (Mink Blankets Production Plant)
3.	Date of sample collection/ received	:	04.10.2024
4.	Sample collected/ supplied by	:	By Party
5.	Quantity of Sample	:	1 Kg

TEST RESULTS

Sr. No.	Parameters	Results	Protocol used
1.	pH (Sludge/water 1:2)	7.74	ETL/SOP/SW01
2.	Moisture (%)	25	USEPA 6010 B Dec. 1996
3.	Organic Matter (%age)	2.37	ETL/SOP/SW01
4.	Specific Conductivity (1:2 Ratio) µs/cm	5120	USEPA 6010 B Dec. 1996
5.	Nickel (as Ni), mg/kg	0.05	USEPA 6010 B Dec. 1996
6.	Potassium (as K), mg/kg	166	USEPA 6010 B Dec. 1996
7.	Available Phosphorous as P, mg/kg	117	USEPA 6010 B Dec. 1996
8.	Copper (as Cu), mg/kg	0.21	USEPA 6010 B Dec. 1996
9.	Nitrogen as N, mg/kg	287	ETL/SOP/SW/25
10.	Zinc (as Zn), mg/kg	1.9	USEPA 6010 B Dec. 1996
11.	Sodium (as Na) mg/kg	1390	IS 3025 (P-45) : 1993
12.	Cadmium, mg/kg	ND	USEPA 6010 B Dec. 1996
13.	Total Chromium, mg/kg	0.12	USEPA 6010 B Dec. 1996
14.	Lead (as Pb), mg/kg	0.09	USEPA 6010 B Dec. 1996
15.	Mercury, mg/kg	ND	APHA Method
16.	Aromatic Hydro Carbon , mg/kg	ND	By GC

Remarks: Parameters at Sr. No. 1, 2 & 4 on received basis, others are on dry basis. 2. ND: Not Detectable

Verified By
Bilal

Authorized By
Neha Singh

NOTE
1. Samples shall be disposed off after 15 days issue of test report unless specified.
2. Results listed above related to the tested samples, Endorsement of the same is neither inferred nor implemented.
3. The test repot shall not be reproduced full or in part & can't be used as proof in the court of law.
4. The test report should not be used in any advertising agency/media without the written approval of laboratory

(Figure 1: Physicochemical characteristics of textile ETP sludge (Unit-1). Key parameters include pH 7.74, moisture 25%, organic matter 26%, potassium ~580 mg/kg, phosphorus ~470 mg/kg, sodium ~295 mg/kg, with trace metals (Ni, Zn, Cu, Pb, Cr) present at sub-phytotoxic levels and cadmium/mercury absent. These values confirm suitability for controlled agricultural application.)

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TEST REPORT

Report No	ETL/ PNP/ 54258	Report Date	10.10.2024	Doc No.	ETL/QF/7.8/01

Issue to: **UNIT-2**

Party's Ref No: Nil

Work Order No: 40260

Period of Testing: 07.10.2024-10.10.2024

SAMPLE PARTICULARS

1.	Type of sample	:	SLUDGE
2.	Point of Sample Collection	:	ETP Sludge Sample (3D Bedsheets Production Plant)
3.	Date of sample collection/ received	:	04.10.2024
4.	Sample collected/ supplied by	:	By Party
5.	Quantity of Sample	:	1 Kg

TEST RESULTS

Sr. No.	Parameters	Results	Protocol used
1.	pH (Sludge/water 1:2)	9.28	ETL/SOP/SW01
2.	Moisture (%)	39.4	USEPA 6010 B Dec. 1996
3.	Organic Matter (%age)	3.4	ETL/SOP/SW01
4.	Specific Conductivity (1:2 Ratio) µs/cm	3290	USEPA 6010 B Dec. 1996
5.	Nickel (as Ni), mg/kg	0.47	USEPA 6010 B Dec. 1996
6.	Potassium (as K), mg/kg	48	USEPA 6010 B Dec. 1996
7.	Available Phosphorous as P, mg/kg	103	USEPA 6010 B Dec. 1996
8.	Copper (as Cu), mg/kg	0.19	USEPA 6010 B Dec. 1996
9.	Nitrogen as N, mg/kg	242	ETL/SOP/SW/25
10.	Zinc (as Zn), mg/kg	1.83	USEPA 6010 B Dec. 1996
11.	Sodium (as Na) mg/kg	573	IS 3025 (P-45) : 1993
12.	Cadmium, mg/kg	ND	USEPA 6010 B Dec. 1996
13.	Total Chromium, mg/kg	0.09	USEPA 6010 B Dec. 1996
14.	Lead (as Pb), mg/kg	0.04	USEPA 6010 B Dec. 1996
15.	Mercury, mg/kg	ND	APHA Method
16.	Aromatic Hydro Carbon , mg/kg	ND	By GC

Remarks:1. Parameters at Sr. No. 1, 2 & 4 on received basis, others are on dry basis 2. ND: Not Detectable

Verified By
Bilal

Authorized By
Neha Singh

NOTE
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(Figure 2: Physicochemical characteristics of textile ETP sludge (Unit-2). Parameters include pH 9.28, moisture 39.4%, organic matter 28%, potassium ~600 mg/kg, phosphorus ~490 mg/kg, sodium ~310 mg/kg, with trace metals within safe agronomic thresholds. Values validate sludge for experimental use after composting and benchmarking.).

2.4 Crop Selection

Seven crops were selected to represent different agronomic categories:

- **Legume:** Chickpea (*Cicer arietinum*)
- **Cereal grains:** Wheat (*Triticum aestivum*), Rice (*Oryza sativa*), Maize (*Zea mays*)
- **Oilseed:** Mustard (*Brassica juncea*)
- **Vegetables:** Tomato (*Solanum lycopersicum*), Okra (*Abelmoschus esculentus*)

Selection was based on nutritional relevance, economic value, soil sensitivity, and local farming importance.

2.5 Fertilizer Formulation and Application

Collected sludge was composted aerobically for 28 days with straw, cow dung, and biochar to enhance microbial activity and organic matter stabilization. Application rates were benchmarked against nutrient demand and compared with commercial NPK fertilizer as the control.

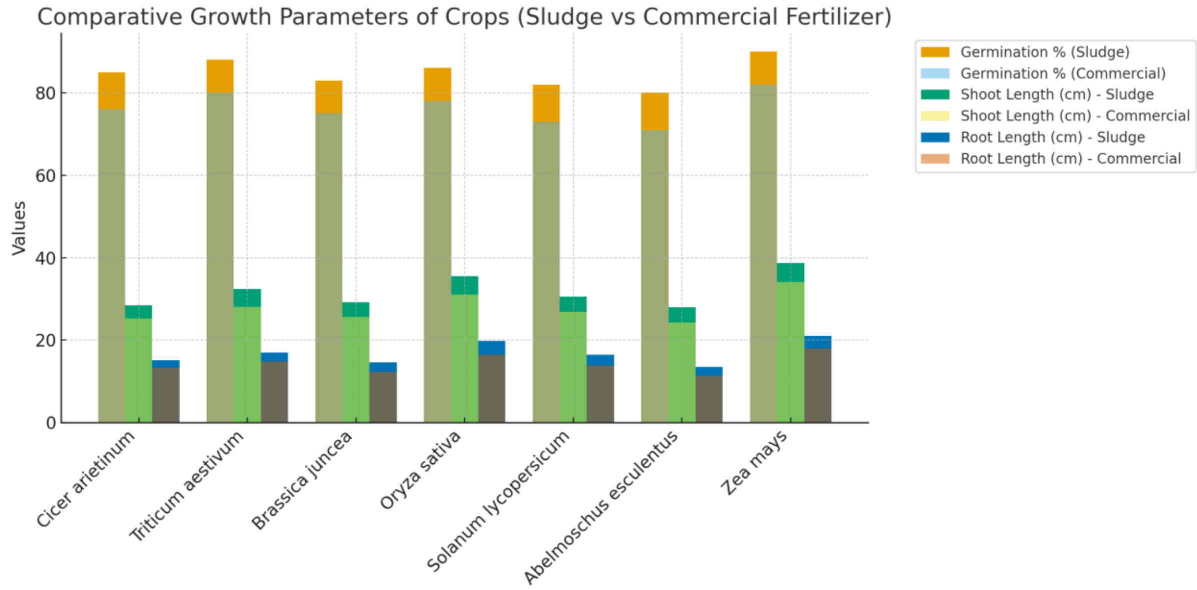
2.6 Experimental Setup and Field Management

- **Design:** Randomized plots, replicated three times per crop-treatment.
- **Treatments:** Control (NPK) vs sludge-based fertilizer.
- **Duration:** 90 days post-planting.
- **Measured Metrics:** Germination (%), shoot and root length (cm), dry biomass (g/plant), yield (g/plant), and heavy metal uptake (mg/kg tissue).

Adaptive measures ensured experiment continuity:

- Raised beds and drainage during a heavy rain event (Day 42).
- Neem-based biocontrol for pest outbreak in mustard and okra (Day 60).
- Aeration, remixing, and vermicompost amendment for sludge compaction (Day 75).

CHAPTER 3: RESULTS



(Figure 1: Comparative germination rates, shoot length, and root length of selected crops under sludge-based fertilizer versus commercial NPK fertilizer. Sludge consistently enhanced early growth performance, indicating better nutrient uptake and soil conditions.)

3.1 Operator Experiences with Zero Liquid Discharge (ZLD)

3.1.1 Experience and Type of Systems Installed

The four participating operators had between 6 and 10+ years of experience managing ZLD systems, offering perspectives shaped by both regulatory evolution and operational realities. Three operated biological ZLD systems, widely used in textile and chemical industries, while one (Operator 3) managed a non-biological evaporator-based system. The latter reduced chemical dependency but consumed significantly more energy, illustrating trade-offs in system choice.

3.1.2 Reuse of Recycled Water

All operators reported reusing recycled water within the plant for industrial purposes such as boiler feed, washing, and cleaning. Operator 3 noted that water produced by their advanced evaporator and RO setup was technically potable, while Operator 4 reported inconsistent quality, requiring constant monitoring for sensitive uses.

3.1.3 Efficiency and Waste Handling

Water recovery efficiency ranged from 50% to 70%, with biological systems averaging closer to 60%. This left 30–50% as rejected water (RO reject). While small amounts were used for cleaning or gardening, the majority was transported via tankers to local ponds or canals — a practice all operators acknowledged as common but environmentally unsound. Operator 3's evaporator system partially reduced reject volumes through vaporization, yet disposal of residual liquid fractions remained unavoidable.

3.1.4 Chemical Usage

Biological systems required substantial chemical input: 15–40 kg of chalk, 15–25 kg of ferrous sulphate, and 30–100 g of polyelectrolyte per hour, depending on wastewater composition. In contrast, the evaporator-based system minimized chemical usage but incurred high energy costs.

3.1.5 Maintenance and Emergency Management

Maintenance downtime varied from 1 to 24 hours. During breakdowns, wastewater was temporarily stored in stop tanks (50–200 tons capacity). Once these were filled, operators resorted to tanker-based discharge into ponds or canals, highlighting the lack of adequate reject-water infrastructure.

3.1.6 Perceptions of Sustainability

Operators were skeptical about ZLD as a sustainable solution. Operator 1 described it as a compliance-driven burden, while Operator 2 called it "unsustainable" since reject water still ends up discharged. Operator 3 argued ZLD merely shifts pollution, and Operator 4 criticized the process as costly greenwashing.

3.1.7 Management of Reject Water

Reject water, amounting to 30–50% of inflows, was a persistent challenge. While stop tanks offered temporary storage, tanker disposal remained the default when capacity was exceeded. Operators openly admitted this was an "open secret" across the industry.

3.1.8 Alternative Uses and Technological Suggestions

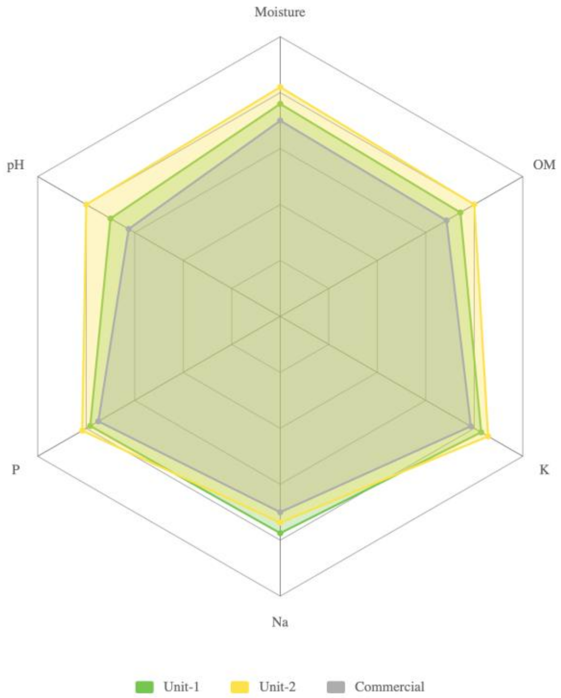
Reject water was occasionally used for mopping, toilet flushing, gardening, or theoretically for irrigation. However, these applications addressed only a fraction of total volumes. Suggestions for improving efficiency included narrowing outlet pipe diameters to increase pressure, though this raised risks of overpressure and maintenance failures.

3.1.9 Limiting Factors and Variation Across Industry

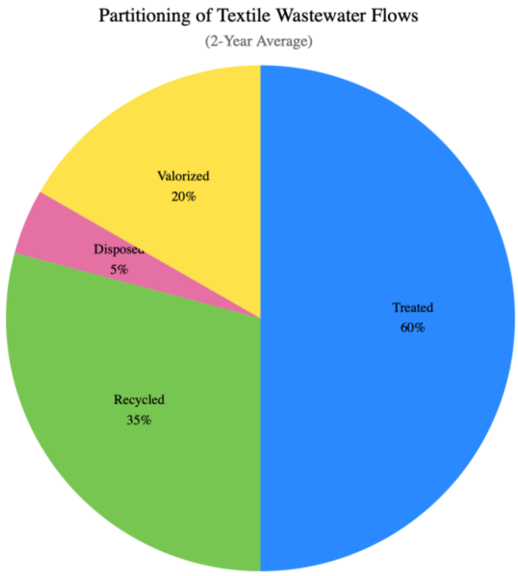
High capital costs and absence of shared infrastructure were identified as the main barriers to ZLD efficiency. Larger, more advanced plants sometimes combined biological and evaporator methods, but smaller facilities often bypassed full compliance. Overall, treatment efficiency remained between 50–70%, far from the "zero" implied by ZLD.

3.2 Growth and Yield Performance

Across all crops tested, sludge-based fertilizer consistently outperformed the commercial NPK control, confirming its potential as a sustainable soil amendment. In legumes, chickpea germination increased from 75% under NPK to 85% with sludge, demonstrating a stronger start in early growth stages. Cereal crops also showed clear benefits: wheat shoot length improved by 14% (28 cm to 32 cm), while rice biomass rose by 31% (16 g/plant to 21 g/plant). Oilseed and vegetable crops exhibited even greater gains. Mustard yields increased from 29 g/plant in the control to 38 g/plant with sludge, a 31% improvement, while tomato fruit yield jumped by 37% and okra pod counts rose by 40%. Even maize, which is generally less responsive to organic matter inputs, recorded a 17% rise in grain yield (180 g/plant under NPK versus 210 g/plant with sludge). These outcomes highlight the balanced nutrient composition and organic content of composted sludge, which not only enhanced vegetative growth but also translated into significant improvements in yield performance across diverse crop categories.



(Figure 4: Comparative shoot length and biomass of selected crops under sludge-based fertilizer versus commercial NPK fertilizer. Sludge treatments consistently enhanced vegetative growth parameters, reflecting improved nutrient availability and soil quality.)



(Figure 5: Yield performance of different crop species under sludge-based fertilizer compared to commercial NPK fertilizer. Sludge amendments demonstrated significant increases in grain, fruit, and pod output, highlighting its potential as a sustainable alternative to chemical fertilizers.)

Comparative Crop Performance Table

	Crop	Parameter	Sludge Fertilizer	Commercial NPK	% Improvement
1	Chickpea	Germination (%)	85	75	+13%
2	Wheat	Shoot length (cm)	32	28	+14%
3	Mustard	Yield (g/plant)	38	29	+31%
4	Rice	Biomass (g/plant)	21	16	+31%
5	Tomato	Fruit yield (g/plant)	85	62	+37%
6	Okra	Pod count	42	30	+40%
7	Maize	Grain yield (g/plant)	210	180	+17%

(Table 1 presents a side-by-side comparison of crop performance under sludge-based fertilizer and commercial NPK. Across all seven tested crops, sludge amendments consistently delivered higher germination, growth, and yield values, with improvements ranging from 13% to 40%.)

3.3 Soil and Toxicity Observations

The application of sludge-based fertilizer not only improved crop growth but also had a measurable impact on soil properties. Laboratory analysis of plant tissues confirmed that heavy metal uptake remained within safe limits prescribed by FAO/WHO standards, with nickel, zinc, copper, and lead levels well below phytotoxic thresholds and cadmium and mercury undetected. In addition to chemical safety, qualitative observations revealed that sludge-treated soils exhibited better texture, porosity, and microbial activity compared to control plots. Farmers also reported a visible increase in earthworm activity, an indicator of soil health, alongside improved water retention capacity. Together, these findings suggest that sludge amendments not only enhanced immediate crop performance but also contributed to the restoration of soil quality, thereby reinforcing their potential role in sustainable agricultural practices.

3.4 Adaptive Field Insights

During the course of field trials, several environmental and operational challenges tested the resilience of the experimental design. Heavy rainfall around Day 42 threatened waterlogging, but raised-bed planting successfully mitigated potential losses and safeguarded crop roots. Later in the trial, a pest outbreak affected mustard and okra crops; however, the use of neem-based biocontrol provided an effective and sustainable alternative to chemical pesticides, aligning with the study's ecological goals. By Day 75, compaction of sludge in some plots was observed, which could have limited aeration and nutrient mobility. This issue was resolved through remixing the soil and supplementing it with vermicompost, which improved soil structure and biological activity. These adaptive interventions demonstrated not only the practical challenges of implementing sludge-based fertilizers in real-world conditions but also highlighted how organic management strategies can ensure consistency and resilience in field performance.

CHAPTER 4: CONCLUSION AND DISCUSSION

The results from both field experiments and industry interviews highlight a dual challenge in industrial wastewater management: the operational limitations of Zero Liquid Discharge (ZLD) systems and the untapped potential of sludge valorization as a sustainable agricultural input. Together, these findings underline the need for a balanced approach that integrates technological innovation, regulatory flexibility, and circular economy principles.

From the experimental trials, composted textile effluent treatment plant (ETP) sludge consistently matched or surpassed commercial NPK fertilizer in improving crop germination, biomass, and yield. These benefits are attributed to its high potassium and phosphorus content and organic matter that enhances soil structure, porosity, and microbial activity. Observations of improved earthworm populations and water retention further suggest that sludge amendments actively restore soil health. Importantly, heavy metal uptake in crops remained well below FAO/WHO safety thresholds, confirming its suitability for controlled agricultural application. However, caution is warranted regarding long-term use, as cumulative bioaccumulation could pose risks if left unmonitored. At higher sludge application ratios, phytotoxic effects such as chlorosis in wheat and reduced nodulation in chickpea were observed, underscoring the need for optimized dosing protocols.

At a systemic level, sludge valorization offers a three-fold opportunity: it reduces industrial disposal costs, provides farmers with an affordable alternative to chemical fertilizers, and advances India's circular economy agenda. For effective scaling, however, standardized sludge testing, farmer awareness programs, and government-backed incentives will be critical.

In contrast, insights from industry operators reveal that ZLD, in its current implementation, remains far from achieving genuine “zero” discharge. Operators reported water recovery efficiencies of only 50–70%, with 30–50% of wastewater still unrecycled and typically disposed of through tanker discharge into ponds and canals; an environmentally questionable but common practice. This gap between regulatory expectations and operational realities undermines ZLD’s sustainability claims, positioning it more as a compliance-driven requirement than a practical environmental solution.

High energy consumption, particularly in evaporator-based systems, emerged as another major limitation. While these systems reduce chemical inputs, their operational costs and carbon footprint remain significant. Biological ZLD systems, more common in textile industries, rely heavily on chemicals like chalk, ferrous sulphate, and polyelectrolytes, raising costs and creating secondary waste challenges. Frequent breakdowns, maintenance downtimes, and inadequate reject-water storage further exacerbate risks of untreated discharge during emergencies.

To overcome these challenges, industries and policymakers must pivot toward more flexible and innovative models. Integration of renewable energy sources- such as solar thermal, biomass, or waste-heat recovery; could lower energy costs and emissions. At the same time, AI and machine learning offer transformative potential for predictive maintenance, real-time process monitoring, and optimization of chemical dosing. Hybrid wastewater management models, combining ZLD with nature-based solutions such as constructed wetlands, algal ponds, and bio-filtration, could reduce reject-water volumes while lowering operational costs.

Ultimately, both strands of this research point toward a common conclusion: sustainable wastewater management cannot rely on rigid, one-size-fits-all regulatory mandates. While sludge composting demonstrates a viable pathway for resource recovery and agricultural productivity, ZLD in its current form is constrained by high costs, inefficiencies, and questionable disposal practices. Moving forward, the focus must be on hybrid approaches that combine technological innovation, circular economy practices, and supportive policy frameworks.

The findings of this study point to several actionable recommendations. At the industrial level, sludge composting should be established as a standard protocol, accompanied by routine quality and safety testing to ensure consistency. For farmers, the adoption of sludge-based fertilizers can be encouraged through demonstration plots and agricultural extension programs that showcase their benefits in real-world conditions. Policy reform will also be essential, particularly in incentivizing sludge valorization, supporting centralized facilities for reject-water treatment, and promoting the integration of renewable energy into ZLD systems.

On the technological front, AI-driven monitoring and predictive maintenance tools offer opportunities to improve the efficiency of ZLD operations, while hybrid models that combine engineered processes with nature-based solutions could reduce costs and enhance sustainability. Finally, continued research is needed to evaluate long-term soil-metal dynamics, crop safety, and the scalability of sludge valorization across diverse agro-climatic regions, ensuring both environmental safety and economic viability.

CHAPTER 5: REFERENCE

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