**Improvement solutions for wastewater Purification Through Smart turbidity assessment**

###  **Abstract:**

Turbidity, a measure of water clarity, serves as a critical indicator of wastewater quality. Turbidity in wastewater is determined by a variety of physical, chemical, and biological factors that impact the concentration and nature of suspended particles. This comprehensive review assesses various methods for measuring turbidity, including nephelometry, spectrophotometry, and transmissometry, examining their respective applications, advantages, and limitations. Additionally, the review discusses key factors that influence turbidity levels, such as industrial effluent, weather events, and the efficiency of treatment processes. Turbidity monitoring is necessary for maximizing treatment processes, environmental compliance, and detecting changes in wastewater quality resulting from outside influences. This review not only provides a comprehensive overview of the current state of wastewater management but also highlights key research gaps, including real-time monitoring challenges, sensor development, and the need for advanced correlations with other water quality parameters. Furthermore, it explores future directions in wastewater management, emphasizing the importance of environmental compliance and sustainability.

**Keywords:** Turbidity, Nephelometry, Spectrophotometry, Transmissometry, Water Quality Monitoring, Smart Sensors.

# 1. Introduction

Water quality assessment is a critical aspect of environmental science, with far-reaching implications for ecological health and human well-being (Vasistha and Ganguly, 2020; Matos et al. 2024). Turbidity is an important parameter employed to measure the quality and clarity of water in environmental and industrial applications. It is defined as the cloudiness or haziness of a liquid due to the presence of suspended particles, including soil, silt, algae, organic matter, or microorganisms. These particles scatter and absorb light, which lowers water transparency and makes it cloudy. Although turbidity is not a direct measure of water quality, it is a critical indicator of the existence of pollutants, sedimentation, or microbial contamination, which can have profound effects on ecosystems and human health (Liao et al., 2015; Thabit, 2024; Hammami et al. 2024).

Various waste waters have different turbidity levels depending on their sources and nature. Domestic wastewater, also known as sewage, comes from residential homes and areas. It has organic material, detergents, food residues, and human excrement, all of which cause moderate to high turbidity. It is necessary to analyze domestic wastewater for turbidity on a routine basis to maximize treatment processes like sedimentation, filtration, and disinfection and to ensure safe discharge or reuse of treated water. Turbidity can be determined manually or with sophisticated sensors, both of which have different uses and advantages. Manual turbidity measurements usually include basic equipment such as a Secchi disk or turbidity tubes. The Secchi disk technique is applied in open water bodies, where the disk is submerged in the water until it cannot be seen, giving a visual approximation of turbidity. Turbidity tubes involve observing the distance of a bottom marker from being visible in a clear tube packed with water. Although these visual techniques are affordable and easy to implement, they are subjective and less accurate compared to new technology (Mueller et al., 2008). Sensor turbidity measurement utilizes nephelometers or turbidimeters that contain a light source and detectors measuring the scattering and absorption of the light by particles in suspension. These sensors yield extremely accurate, real-time measurements and are applied extensively in water treatment facilities, environmental monitoring, and industrial processes. Contemporary turbidity sensors also can be integrated into automated systems, allowing continuous monitoring and notifying operators of water quality changes. In combination, manual and sensor-based methods provide complementary means of turbidity measurement, trading off accessibility and accuracy (Kol Latsch et al., 2000).

**2. WASTEWATER CHARACTERISTICS**

**2.1 Industrial Discharges**

Industrial effluents have major influences on turbidity levels of water bodies and are a key factor for turbidity monitoring systems. Such effluents usually add suspended solids, chemicals, and other contaminants that enhance water cloudiness, affecting its quality and the health of aquatic ecosystems. Real-time monitoring is crucial for controlling the turbidity due to industrial effluents (Narasimhan et al., 2017), describe how continuous turbidity monitoring systems, with sensors installed in water bodies, offer useful real-time information. These systems allow for the identification of abrupt turbidity increases, typically resulting from industrial effluents, enabling timely interventions to avoid environmental damage (Smith et al., 2019).

**2.2 Environmental Events**

Natural events like intense rainfall and floods greatly increase turbidity levels by bringing sediment, organic materials, and other particles into water bodies. Soil erosion and runoff from the surface during such events add to the increased suspended solid load (Carson et al., 1962), and highlight the need for incorporating hydrological information into turbidity monitoring systems to differentiate between natural and human-related sources. This distinction is important in formulating targeted strategies to deal with water quality during severe weather conditions (Johnson et al., 2020).

**3. TURBIDITY IN WASTEWATER**

The Turbidity sensor measures cloudiness or haziness in the water, caused by particles in water that are not visible to the naked eye (Jain et al., 2021). The sensor employs the detection of suspended solids in water by calibrating the transmittance of light and rate of scattering of light and is modified concerning the water quality of total suspended solids (TSS), the value considered safe for the measurement of human body from 0 to 5 NTU. The aspect that this measurement sensor can be regulated by the filters, to prevent health problems owing to the high level of suspended solids (TSS) in water (Adv et al., 2019). Human activities are the principal reason for turbidity in water. A few industries like mining and agricultural activities result in the movement of particles and get contaminated with water. It is due to suspended or dissolved substances such as clay and silt fine organic and inorganic substances, soluble coloured organic substances, algae etc. If the turbidity of water is higher it impacts human health (Ezzati et al., 2014). In water bodies like lakes, rivers and reservoirs high turbidity can decrease the quantity of light which can penetrate up to the lower depth of submerged aquatic plant species. It also influences the capacity of fish, and shellfish gill to uptake the DO (dissolve oxygen) (Fenton., 2008).



**Fig. 1. Turbidity Meter (TBD-99) (** [**https://www.dongrun-instrument.com/product/low-range-laser-turbidimeter/**](https://www.dongrun-instrument.com/product/low-range-laser-turbidimeter/)**)**

### **4**. **METHODS FOR TURBIDITY ASSESSMENT**

**4.1 Nephelometric turbidity unit**

In order to determine the correlation functions between turbidity and the main pollutants, 25 sampling sessions weather, and the remaining 21 were carried out during various rainfall events. The four monitoring points were also provided with turbidimeters and flow meters. The turbidity sensor is a Viso Turb 700 IQ electrode (WTW, Munich, Germany), which measures turbidity in the range of 0–4000 NTU (nephelometric turbidity unit). The average turbidity value is every 5 min calculated from the integration of 15 s of data. On-site calibration is verified with kieselguhr, and no sensor drift was detected during the experiment (Le Heche et al., 2015). A flow meter (Hydrae, Lyon, France) based on the acoustic Doppler principle measured the flow at the monitoring point, and the rainfall data were monitored by a tipping bucket rain gauge in the Tongzhi study area. To monitor the other water quality parameters (excluding turbidity), a sample was taken in the combined sewer every 5 min at the start of the rainfall, and the interval of subsequent sampling was 10–15 min. The particular operation was based on the rainfall intensity. The samples were carried to the laboratory in polyethene bottles and refrigerated at 4 °C prior to testing (Bensinger et al., 2015). Total dissolved solid alters the taste and colour of water. It also impacts the health of human beings due to the presence of potassium cations, carbonates, chloride, sulphate nitrate anions etc. The ranges of TDS in various water bodies are, 500 ppm for fresh water, 500-30000 ppm for brackish water and 30000-40000 ppm for saline water (Raza et al., 2020).

**Table 1. Properties of turbidity assessment in the Nephelometric method**

|  |  |  |
| --- | --- | --- |
| **Parameter** | **Unit** | **Maximum Permissible value** |
| **PH** | \_ | 5.5-9.5 |
| **Temperature** |  | 45 |
| **Turbidity** | NTU | 5.0 |
| **Colour** | TCU | 15 |
| **Total dissolved solid** | mg/1 | 500 |
| **Mercury** | mg/1 | 0.01 |
| **Arsenic** | mg/1 | 0.02 |
| **Cadmium** | mg/1 | 1.0 |
| **Lead** | mg/1 | 0.01 |

**4.2 Spectrophotometry**

Spectrophotometry is an analysis technique measuring absorbed light from suspended particles within a sample. The method works excellently when working with turbid and coloured samples, rendering it a priceless utility in a multitude of analysis arenas (Conner et al., 1974). The best part of using spectrophotometry is detecting a diverse selection of particles within even highly compounded samples based on their absorption of light. It is not all smooth sailing though. In highly turbid samples, the measurement might have to be made after dilution, which would make the analysis more difficult and introduce possible causes of error (Wang et al., 2019).The real-time monitoring of wastewater parameters is a great scientific and technical challenge because of the fluctuation of wastewater properties as well as the harsh physical-chemical conditions to which the sensors are exposed. Optical methods such as UV–V spectroscopy and near-infrared spectroscopy NIR have been applied to consistently determine solids, organic matter and nitrates in wastewater for more than a (Ahmad Fairuz Bin Omar, 2015). UV–Vis is the interaction between samples and radiation in the 200–780-nm wavelength range at single or multiple wavelengths to estimate a number of parameters. It is quick, non-destructive and environment-friendly as it does not involve chemicals to be added. It is combined with multivariate data analysis like partial least squares (PLS) regression to produce a regression model from spectral data to predict the water quality parameters (Chen et al., 2020).

**4.3 Transmissometry**

Transmissometry is a technique that measures the loss of light upon passing through a sample. The method works best in low-turbidity conditions where the transparency of the sample permits a simple measurement of light transmission (Conner et al., 1974). Transmissometry is applied extensively for uses involving clear or very lightly turbid waters. Transmissometry is not efficient with highly turbid or coloured waters. In those conditions, absorption and light scattering can significantly degrade the performance of measurements, with poor results and reduced efficacy **(Wang et al., 2019).** Transmissometer is a method applied to quantify the turbidity or transparency of a liquid by measuring light passing through a sample. It is usually utilized in several water quality monitoring processes, such as wastewater treatment and environmental observation. The basis of transmissometer is on the interaction between particles suspended in water and light (Ahmad Fairuz Bin Omar, 2015). Particles in water scatter and absorb light when directed through a water sample, with the amount that reaches the detector being less. The extent to which light gets attenuated depends on the amount of suspended particles, which offers an approximation of the turbidity of the water. This technique is especially beneficial for real-time water quality monitoring, as it permits continuous turbidity measurement without requiring time-consuming sample preparation or the use of chemical reagents (Marie-Florence Pouet et al., 2015). Transmissometer may be combined with other analytical methods to give a more complete picture of water quality. For example, when combined with sophisticated sensors and data analytics, transmissometer can be employed to monitor turbidity variations over time and evaluate the performance of water treatment processes. It is also beneficial in identifying unexpected water quality variation, for example, a sudden increase in sediment or pollutant content, which could have important environmental or health implications (Mohd Zubir Mat Jafri et al., 2015).

**4.4 Advanced Techniques**

Advanced methods, including Laser Diffraction and Real-Time Monitoring Sensors, provide more advanced functionality for particle analysis. Laser Diffraction is especially beneficial in providing in-depth particle size analysis, providing useful data on the size distribution of particles in a sample (Shaurya Swami et al., 2023). It does have a major drawback: it is too expensive, which might restrict its universal application in some environments. Real-Time Monitoring Sensors, however, have the potential for ongoing data collection, which could transform monitoring systems. Though promising, these sensors continue to struggle with robustness and accuracy, necessitating further development before they can be trusted for accurate and reliable real-time measurements (Noble et al., 2018). State-of-the-art turbidity measurement of wastewater has markedly progressed to optimize precision, in-situ observation, and constancy under unpredictable environmental conditions. Laser and light-based methods like nephelometry (according to ISO 7027 standards) and laser diffraction are largely employed to assess light scattering of suspended particles for obtaining accurate turbidity information. Ultrasonic methods, such as ultrasonic attenuation and acoustic Doppler velocimetry (ADV), are successful in the case of high-turbidity conditions in which optical sensors are likely to fail, as these examine sound wave reflections to calculate particle concentrations. Spectroscopic techniques like UV-Vis and near-infrared (NIR) spectroscopy have the benefit of determining turbidity and other water quality indices at the same time by monitoring light absorption in certain wavelengths. In addition, machine vision and image processing systems combined with artificial intelligence (AI)-driven algorithms facilitate real-time particle concentration and distribution analysis in wastewater samples. Micro-electro-mechanical systems (MEMS)-based sensors and hybrid technologies combined further augment monitoring, providing compact, low-power solutions for continuous monitoring. Data-driven methods, for example, machine learning algorithms and cloud-based monitoring systems, are being used more and more to forecast turbidity patterns and aid proactive management in wastewater treatment systems. These new methods collectively enhance the effectiveness and efficiency of wastewater quality monitoring (Shaurya Swami et al., 2023).

#### **Table 2.** Comparison of Methods

| **Technique** | **Strengths** | **Limitations** |
| --- | --- | --- |
| Nephelometry | High sensitivity | Ineffective for coloured samples |
| Spectrophotometry | Multi-parameter use | Expensive equipment |
| Transmissometry | Simple and cost-effective | Limited to low-turbidity samples |
| Advanced Sensors | Real-time capability | High costs and maintenance needs |

### **5. FACTORS INFLUENCING TURBIDITY**

Turbidity is a condition of haziness or cloudiness in water due to suspended particles (Martinez et al., 2021),whose origin may be natural or through human activities. Some of the main factors of turbidity include soil erosion that deposits silt and clay in water bodies, and urban runoff carrying contaminants like oils, metals, and debris. Algal blooms, most of which arise due to enrichment by nutrients, also play an important role in contributing to turbidity. Industrial effluent, wastewater, and dredging operations further enhance the suspended particle concentration. Natural phenomena such as floods or heavy rainfall can resuspend sediments, increasing turbidity levels for a short period. Also, decomposition of organic materials and aquatic activities such as boating or fishing can resuspend sediments, causing turbidity to rise. Control of these factors is essential for water quality maintenance and aquatic ecosystem health (Anderson et al., 2023). Turbidity in wastewater is determined by a variety of physical, chemical, and biological factors that impact the concentration and nature of suspended particles. Suspended solids, which comprise inorganic materials such as silt, clay, and mineral particles, and organic matter such as plant material and microbial biomass, are among the major factors. The size, shape, and density of these particles significantly impact light scattering, with smaller particles generally causing higher turbidity. Microbial activity also plays a role, as the growth of algae, bacteria, and protozoa, particularly in nutrient-rich environments, contributes to turbidity levels (Mandal et al., 2014). Chemical composition is another important consideration; dissolved materials such as iron, manganese, and metal oxides may precipitate under specific conditions to form colloidal particles, and coagulant and flocculant residues from water treatment can further impact turbidity. Hydrodynamic conditions like high flow rates or turbulence can resuspend settled matter, raising turbidity, while low flow conditions might enable particles to settle and lower it (Djobbi et al., 2018).Temperature variations influence the solubility of gases and particle behaviour, affecting aggregation or dispersion, and thermal stratification in storage tanks can result in turbidity variations at varying depths. Moreover, pH affects the dissolution or precipitation of chemicals, with very high or very low pH levels favouring particulate formation. High organic loads such as oils, greases, and natural organic matter contribute to increased turbidity when they create emulsions or colloidal suspensions. Finally, industrial and human actions, like releases from urban runoff, construction, and industrial operations, introduce sediments and a wide variety of pollutants that enhance fluctuating turbidity levels within wastewater systems (Ben Hassen et al., 2018).

**5.1 Treatment Plant Efficiency**

The performance of water treatment plants has a direct impact on turbidity levels in treated water. Technical problems, such as inefficient coagulation, sedimentation, or filtration processes, can lead to high turbidity through the inability to eliminate suspended particles (Dundovic and Srdoc, 2024),emphasize the significance of advanced monitoring systems in assessing treatment plant performance. Through real-time detection of inefficiencies, these systems enable operators to maximize processes for ensuring water quality standards. Ongoing inspection of treatment operations is required for regulatory compliance and protection of the public's health (Carter et al., 2010). The performance of a wastewater treatment plant can be determined by a wide range of factors that include treatment processes type, the influent wastewater characteristics, and the prevailing working practices. Treatment processes like physical, chemical, and biological are combined to eliminate pollutants from the water, with the efficiency of each depending on the type of pollutants in the water. Plant performance is largely influenced by influent quality, such as the concentration of organic matter, suspended solids, and industrial discharges (Nawaz and Ali, 2018). Advanced technologies such as automation and real-time monitoring systems aid in maximizing treatment efficiency by identifying operational problems and making adjustments to processes. Other operational aspects such as maintenance, qualified staff, and efficient process management also enhance efficiency. Another consideration is the energy usage of the plant since energy-efficient processes not only lower costs but also make operations more sustainable. Finally, whether the plant is capable of fulfilling regulatory water quality requirements and providing high-quality effluent is the most important index of its efficiency (Wang, 2019).

**6. IMPLICATIONS**



**Fig. 2. Workflow progress**

**6.1** **Trends in turbidity levels**

Turbidity concentrations undergo dramatic changes during the multiple treatment phases, including primary, secondary, and tertiary treatment. In the primary phase, suspended solids are eliminated via sedimentation, resulting in a preliminary decrease in turbidity. In the secondary treatment stage, biological degradation further breaks down organic content, causing further turbidity reductions. The third stage of treatment, comprising highly advanced filtration and chemical processes, produces the lowest turbidity values and guarantees water quality compliance with strict regulatory limits. According to Since understanding these trends is important for maximizing treatment plant performance and guaranteeing water quality compliance (Jackson et al., 2021). Trends in turbidity levels in wastewater are influenced by a variety of factors, including seasonal variations, weather patterns, and changes in wastewater composition.

Turbidity levels will usually rise during rainfall or snowmelt conditions due to stormwater runoff inflows, which are laden with suspended solids, sediments, and organic material entering wastewater facilities. Industrial operations and construction work may also contribute particulate material into the waterbody, thereby fluctuating the level of turbidity (Green and Wang, 2022). In certain areas, seasonal farming activities, like fertilization and irrigation, may cause turbidity to rise due to soil erosion and runoff carrying sediments into treatment plants. Long-term turbidity trends may also indicate technological advancements in wastewater treatment, such as the use of more sophisticated filtration and coagulation processes, which could lead to lower and more stable turbidity. Turbidity monitoring is necessary for maximizing treatment processes, environmental compliance, and detecting changes in wastewater quality resulting from outside influences (Green and Wang, 2022).

**6.2 Implications for process optimization**

Turbidity measurements are critical in optimizing water treatment operations. Turbidity monitoring enables operators to adjust the dosing of coagulants and flocculants in coagulation-flocculation processes to effectively aggregate particles and settle those. Continuous turbidity measurement can also detect equipment failure, including filter clogging or poor sedimentation, that may affect water quality. As reported by, the integration of real-time turbidity measurements into process control systems increases efficiency and saves costs on chemical overuse and maintenance (Roberts et al., 2020)**.** The implications for process optimization in wastewater treatment are great, as enhanced efficiency and effectiveness of treatment processes can result in improved water quality, cost savings, and improved environmental protection. By monitoring the important parameters like turbidity, pH, and chemical oxygen demand (COD) in real-time, treatment plants can modify operating variables in real-time to achieve optimal performance. Process optimization can include the utilization of cutting-edge technologies such as automated sensors, artificial intelligence, and data analytics to anticipate impending problems and optimize chemical dosing, filtration, and aeration rates. Furthermore, embracing energy-saving practices not only curbs operating expenses but also lowers the environmental impact of wastewater treatment. Through process optimization methods, treatment facilities are able to improve contaminant removal capacities, increase effluent quality, and meet more stringent environmental standards, finally generating sustainable water management and resource recovery (Green and Wang, 2022).

**6.3 Environmental and Regulatory Considerations**

Turbidity has enormous environmental and regulatory consequences. Regulatory agencies place severe requirements on turbidity levels for the discharge of effluent to safeguard aquatic life and preserve water quality. For instance, the U.S. Environmental Protection Agency (EPA) requires turbidity restrictions for wastewater treatment facilities in order to reduce the effect on the receiving water bodies (Robert et al., 2020). High turbidity in natural water systems can limit the penetration of light, negatively impacting photosynthesis among aquatic vegetation and destabilizing the food chain. It also affects aquatic creatures by occluding fish gills and changing habitats. A study highlights how compliance with regulatory turbidity standards is necessary to protect aquatic ecosystems and facilitate sustainable water resource management (Green and Wang, 2022). Environmental and regulatory factors are important factors in the design, operation, and optimization of wastewater treatment plants. With more stringent regulations, treatment plants must be able to meet higher effluent quality standards to safeguard aquatic environments, public health, and environmental quality in general. These standards usually limit pollutants like nitrogen, phosphorus, heavy metals, and pathogens, which should be removed from wastewater effectively before it is released (Chaubey and Singh, 2021). Compliance with such standards is not just legally obligatory but also a vital aspect of reducing the effect of wastewater releases on nearby water bodies. Environmental aspects also include green practices, such as energy-saving technologies, recovery of resources (such as biogas and recycling of phosphorus), and minimizing carbon footprints. Green technologies and practices enable treatment plants to contribute to larger environmental objectives, including greenhouse gas emission reduction and natural water resource conservation. Furthermore, treatment facilities are required to remain current on developing regulatory systems, which could be altered by emerging scientific findings or environmental issues, in order to remain compliant and continue reducing their footprint on the environment (Abyar and Rahman, 2023).

### **7. RESEARCH GAPS**

**7.1 Real-time monitoring challenges**

Real-time turbidity monitoring is extremely challenging, especially in dynamic and highly variable systems like combined sewer systems. Sensors tend to lose accuracy when turbidity changes occur very quickly as a result of stormwater entry or industrial releases (Ullo and Sinha, 2024). Even conventional optical sensors are prone to fouling, calibration drift, and difficulty distinguishing between particulate and non-particulate causes of turbidity. According to, enhanced sensor design and strength are imperative for increasing the reliability of real-time turbidity measurement under these circumstances (Williams et al., 2021).

Real-time monitoring of wastewater treatment has some challenges in spite of its tremendous potential for increasing operational efficiency and regulatory compliance. One of the main challenges is the variability and complexity of the characteristics of wastewater, which change considerably due to variations in influent composition, seasonal changes, and unforeseen events like industrial discharges or storms. This heterogeneity complicates the achievement of consistent, precise real-time measurements with current sensors and monitoring systems (Villez et al., 2020). Moreover, most traditional sensors are prone to fouling, calibration drift, and interference from other chemicals in the wastewater, which can result in erroneous readings and frequent maintenance. Data management is a challenge, with real-time monitoring producing significant amounts of data to be processed, analyzed, and interpreted rapidly for decision-making purposes. Integration with control systems and predictive models also makes the process more complex and demands solid software platforms and capable personnel to translate results. In addition, the expense of state-of-the-art sensor technologies and their integration in treatment plants is a hindrance, particularly for small or financially limited facilities. Overcoming these issues demands constant innovation in sensor technology, data analysis, and system integration to improve the reliability, cost-effectiveness, and scalability of real-time monitoring of wastewater treatment (Dhruba, 2023).

**7.2 Correlation with other water quality parameters**

Though turbidity is a commonly monitored water quality parameter, there is scant research establishing its direct association with other such important parameters as Total Suspended Solids (TSS), Biological Oxygen Demand (BOD), and Chemical Oxygen Demand (COD) (Gupta et al., 2021). It is necessary to study these associations so that turbidity data can be used as a proxy for assessing overall water quality. For example, indicated that turbidity tends to be highly correlated with TSS, but the correlation is a function of particle size and composition, so site-specific studies are required for practical application (Smith et al., 2019).

The relationship between turbidity and other water quality parameters is essential in determining the general health of water systems and maximizing treatment processes. Turbidity, which is commonly employed as an indicator of suspended solids in water, is highly related to parameters such as total suspended solids (TSS), biochemical oxygen demand (BOD), and chemical oxygen demand (COD). Increased turbidity usually indicates a rise in the level of organic matter content, sediments, and contaminants, which may result in elevated BOD and COD levels (Das, 2015). The correlation is significant for predicting the likelihood of oxygen depletion in water bodies since organic matter can cause the oxidation of oxygen during its decomposition. Moreover, turbidity is usually associated with the content of nutrients such as nitrogen and phosphorus because turbidity-related particles can also transport these nutrients. Another issue related to water is the presence of pathogens, where the high turbidity is a suitable medium for microbial development and, therefore, a key parameter in determining the safety of water. With this understanding of the correlations, monitoring systems can forecast the behaviour of various parameters all at once and employ more efficient treatment approaches, i.e., optimize chemical dosing or filtration methods in order to treat multiple contaminants simultaneously (Jena et al., 2020).

**7.3 Advanced measurement techniques**

Even with technological advancements in turbidity measurement techniques, the uptake of advanced methods such as laser diffraction is still low (Boku Instrument, 2021). The techniques are expensive, complex to operate, and require specialized skills to discourage extensive usage, particularly in resource-constrained environments. Further, the absence of miniaturized and low-cost turbidity sensors limits applications in field deployment in remote or decentralized monitoring systems. , the innovation of portable, low-cost, and energy-efficient turbidity sensors is imperative to overcome these hurdles and enhance the accessibility of sophisticated measurement techniques (Chen et al., 2020). Sophisticated measurement methods in wastewater treatment have immensely improved the capability to monitor and regulate water quality with increased accuracy and efficiency. Conventional techniques of water quality measurement, including grab sampling and laboratory testing, tend to be time-consuming and labour-intensive. However with the introduction of technologies like online sensors, optical sensors, and real-time data analysis, wastewater treatment plants can now instantly measure important parameters like turbidity, pH, dissolved oxygen, and chemical concentrations (Sharma et al., 2024). Optical techniques such as UV–V is spectroscopy and near-infrared (NIR) spectroscopy are commonly utilized for their capability to offer fast, non-destructive, and precise measurements of organic compounds, solids, and nitrates in wastewater. The techniques coupled with multivariate data analysis procedures such as partial least squares (PLS) regression enable exact estimation of water quality parameters using spectral data (Zhu et al., 2004). Other new technologies, including electrochemical sensors, remote sensing, and biosensors, provide other benefits of sensitivity, portability, and automation, which further improve the ability to continuously monitor wastewater systems. With the combination of these new measurement technologies with automated control systems and predictive modelling, treatment plants can maximize processes in real time, lower energy usage, increase operational efficiency, and meet environmental regulations (Thompson et al., 2022).

**7.4 Impact of Emerging Pollutants**

The effects of the newly emerging contaminants such as microplastics, pharmaceuticals, and nanomaterials on turbidity have been less understood. Such contaminants normally appear in colloidal or particulate forms that enhance turbidity, whose influences are not known by conventional monitoring techniques. The literature emphasizes the immediate need to investigate the magnitude of contributions made by emerging pollutants towards turbidity and assess their health and environmental impacts on water bodies (Jones et al., 2019).

**7.5 Turbidity in non-conventional water sources**

Literature on turbidity dynamics in non-traditional water sources, including greywater, blackwater, and industrial wastewater reuse systems, is limited (Jain and Das, 2017). These sources tend to have distinctive turbidity profiles due to varied contaminants and treatment processes. In a review, it is important to understand turbidity in these systems to optimize reuse practices and meet water quality standards. Extending the range of turbidity studies to cover non-conventional sources will contribute to the growth of sustainable water management practices (Chen et al., 2020). Turbidity in non-conventional water supplies, including stormwater, wastewater, desalinated water, and reclaimed water, is a significant quality factor that needs proper monitoring and control. Non-conventional water sources are being studied and used increasingly to augment freshwater resources, especially in water-scarce areas. Yet, these sources are usually characterized by higher turbidity because of suspended solids, organic particles, pollutants, and microbial contaminants. Stormwater runoff, for instance, may transport sediments, trash, and pollutants from urban areas, resulting in elevated turbidity (Clark and Hakim, 2015). Likewise, wastewater and reclaimed water may be associated with suspended particulates, bacteria, and nutrients that can cause turbidity. The high turbidity in these unconventional water sources can be problematic for treatment operations, especially filtration, disinfection, and compliance with water quality standards. Turbidity is frequently employed as a surrogate measure for other contaminants, including pathogens, and thus is an important parameter for guaranteeing the safety and acceptability of these water sources for reuse. Sophisticated treatment methods, including filtration, coagulation, and flocculation, are generally used to minimize turbidity and enhance the quality of non-conventional water. Measurement of turbidity levels is necessary to optimize treatment operations and guarantee that reclaimed or desalinated water complies with regulatory requirements for safe use in irrigation, industrial applications, or even potable water supply systems **(Sanchez-Flores et al., 2018).**

### **8. CHALLENGES AND FUTURE DIRECTIONS**

**8.1 Challenges**

Turbidity monitoring in wastewater systems is fraught with a number of challenges, largely because of the heterogeneity in turbidity sources and composition between industrial and municipal wastewater systems. Industrial effluents, for instance, can introduce a combination of organic and inorganic solids (Smith et al., 2019), chemicals, and other pollutants, which can be vastly different from those in municipal wastewater. This heterogeneity makes turbidity sensor calibration and performance difficult, resulting in issues with obtaining consistent and precise monitoring in various systems (Alemu et al., 2018). Moreover, most sophisticated real-time monitoring technologies like laser diffraction and other particle size analysis methods are expensive and need maintenance often, making them less accessible for use in regular processes. The high initial cost and operational complexity of these technologies render them less accessible, particularly for small treatment plants with limited financial resources (Chen et al., 2020). Wastewater treatment challenges are varied and complex, including technical, operational, environmental, and regulatory dimensions. Among the major challenges is the variability in wastewater characteristics that can change remarkably depending on factors like weather patterns, industrial production, and time of year (Naidoo et al., 2013). Such changes complicate uniform monitoring and treatment of wastewater necessitating adaptable and flexible treatment protocols. Furthermore, old infrastructure within most treatment facilities is a real challenge, leading to inefficiency, high maintenance costs, and the necessity of expensive upgrades. The existence of new contaminants, including pharmaceuticals, personal care products, and microplastics, has also made wastewater treatment more challenging, as these compounds are resistant to traditional treatment processes (Naidoo et al., 2013).

**8.2 Future Directions**

The future of turbidity monitoring in wastewater treatment is the creation of cheaper and more rugged sensors, especially those that can continuously monitor hostile environments. These sensors must be able to handle extreme temperatures, chemical contact, and other harsh conditions that are common in wastewater systems. To meet these demands, upcoming studies may emphasize sensor miniaturization and the use of new cost-effective materials with fouling- and degradation-resistance (Smith et al., 2019). In addition, the intersection of the Internet of Things (IoT) and Artificial Intelligence (AI) holds a promising key to the further development of turbidity analysis. IoT-based turbidity sensors might send real-time information to central systems, which could be analysed automatically by AI algorithms to identify trends, abnormalities, and inefficiencies in the treatment process (Even et al., 2004). This would allow predictive maintenance, chemical dosing optimization, and overall process efficiency improvement. In addition, the creation and standardization of new techniques for turbidity measurement, including laser diffraction and dynamic light scattering, may render these technologies standard equipment in wastewater treatment plants, delivering more accurate and consistent information for regulatory compliance and environmental conservation (Baker et al., 2021).

### **9. CONCLUSION**

Estimation of continuous concentrations of the pollutants in the CDAPP's sewage system based on turbidity and conductivity measurements has been successfully validated and functioning for a number of months. It made it easier to monitor wastewater. The instantaneous and continuous estimation of pollutant concentration can be obtained which is highly attractive for the sanitation manager. This study then analyzed various methods for processing the data. The raw data study makes it possible to have a general monitoring and behaviour of sewerage. Yet, from this data, pollutant fluxes can be computed daily. This makes it possible to summarize the information and to treat large data sets (month, year) to arrive at a global monitoring which can take into consideration all situations (weather, activities, seasons) that are met in the study area. Additionally, such a presentation permits the facile distinction between wet and dry phases, among different rainfall events.

**Conference details:**

2nd National Horticulture Conference (NHC 2025) on Regenerative Horticulture: Accelerating Sustainable Horticulture Production, Kalasalingam School of Agriculture and Horticulture, KARE, Krishnankoil, Tamil Nadu, India, 20 & 21 of March 2025.

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