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Advancements in Sustainable Water Treatment Technologies: Innovations and Future Directions

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Abstract

With the increased demand of environmentally friendly and efficient methods of treating wastewater pollutants, the world is drifting towards new methods of treatment of wastewater that are integrated and curb the shortcomings of the old systems. The conventional methods are ordinarily ineffective to eliminate emerging pollutants, apply fewer resources, or acquire environmental sustainability objectives. A combination of nanotechnology, bio-based filtration, membrane systems, advanced oxidation processes (AOPs) and artificial intelligence (AI) promise to offer a novel means of water cleaning up.A mixture of comparisons and experiments are utilized in this research, in which the performance of different treatment technologies is examined. These are hybrid membrane-biofiltration systems, nanomaterial-enhanced adsorptive media and AI-based process control units. Their approach combines lab-scale simulations with performance prediction models as well as data analytics to consider the energy-use, removal and cost-effectiveness.It was established in the results format that nanofiltration systems could remove over 95% of these contaminants and the bio-based filters could consistently eliminate the heavy metals and nitrates. AOPs worked quite well when they were accompanied by membranes in breaking down recalcitrant chemicals. Nevertheless, it is very crucial to optimize the use of energy. Very accurate predictions were made by AI-based models on the effectiveness of the system, and that is why it was possible to change it in real time, and operations in different situations become more robust.The findings reveal that the integrated treatment systems are found to be better compared to the standalone ones in being able to remove pollutants, scoring on the sustainability index and being cost-effective. These findings demonstrate the significance of this approach to the application of multiple technologies in order to achieve the Sustainable Development Goals (SDG-6), and particularly in those areas where resources are limited and fragmented.Finally, we find in our research that application of smart, hybrid and green wastewater treatment technology is feasible and even essential. The report provides a helpful asset plan regarding infrastructure development in future. It requires individuals in diverse sectors to collaborate, modifications in the regulations and massive implementation of clever treatment structures so as to safeguard the water reserves of the world.

Keywords: “Water Treatment”, “Sustainability”, “Innovations”, “Advanced Filtration”.

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INTRODUCTION

The increased demand of clean water around the world and the increased threat of environmental destruction has only intensified the requirement of using improved and more sustainable wastewater treatment technology. Old water-treatment methods are typically not effective when it comes to the elimination of emerging contaminants or the maintenance of the evolving requirements of nowadays society. Consequently, environmental policy and engineering debates are demanding that people shift towards more effective solutions that are more environmentally friendly and flexibility (Zhang et al., 2021; Kumar et al., 2022).Advanced concepts such as membrane filtration systems and bio-based filter processes have been in the spotlight a great deal. Two illustrations of membrane technologies that are quite effective in separating salts and micropollutants include reverse osmosis and nanofiltration. However, challenges of membrane fouling, energy consumption, and affordability remain significant (Ali et al., 2020). A cheaper and easily available biologically-based technology like biochar and artificial wetlands, which are capable of degrading pollutants in a natural way, as well as retaining heavy metals, is gaining popularity (Rahman et al., 2022; Singh et al., 2023). These technologies do not only contribute to more environmental friendly wastewater treatment, they also facilitate resource recovery and the circular economy approach.Advanced Oxidation Processes (AOPs) that rely on the formation of highly reactive molecules such as hydroxyl radicals also have been significant components in the reductive strategies of recalcitrant organic molecules (Chen et al., 2021). Some of the technologies that have proved to be quite effective in destroying drugs, pesticides, and other complex pollutants that cannot be easily eliminated using conventional biological treatment include photocatalysis, ozonation, and Fenton-based oxidation (Yuan et al., 2022; Zhao et al., 2021). However due to the high cost of running AOPs and the large amount of energy used, we must seek systems that can interact with low cost filtering or adsorption technologies.In the past several years, nanotechnology has transformed the manner in which we clean up the environment because engineers are able to construct materials which perform highly at very the small scale. Nanomaterials such as carbon nanotubes, metal oxides and magnetic nanoparticles are large in surface area with adjustable surface chemistry and more reactive. The properties render them very effective at removing many sorts of pollutants in the wastewater (Patel et al., 2022; Hussain et al., 2023). They implemented on membranes, catalysts, and adsorbents make the process of capturing them extraordinarily easy and selective.

All the progress notwithstanding, there remain certain gaps in our knowledge. The number of field-scale demonstrations of integrated treatment systems is not large, and the issue of scalability remains substantial. In addition, new technology does not always match with the rules and regulations and popular approval making it quite difficult to adopt water treatment methods (Iqbal et al., 2021). Pilot studies, as well as life-cycle studies should pay

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a great attention to economic feasibility, long-term reliability and environmental safety of the project.This paper is aimed at taking a closer look and compare the recent advancements in technologies of treating water in an environmentally friendly manner

METHODOLOGY

One of the most promising directions in management of water throughout the modern sustainable practice has become membrane filtration and bio-based filtration systems. The desire to have efficient, effective and environmental friendly water purification technologies owing to the rising number of challenges associated with the lack of water, water pollution and energy demands has addressed the need of these innovations. This category dwells in the innovations in membrane filtration such as)_ and reverse osmosis (RO) and ultrafiltration (UF) and the use of bio-based filtration solutions like biochar and biofilms. It also describes how the two systems combine to maximize the performance of water treatment.Membrane filtration entails the usage of semi-permeable membranes to eliminate water contaminants. The technology has become popular in many industrial and municipal water treatment facilities because of its high efficiency, a wide spectrum of contaminants, and contaminants removed as well as relatively low cost of operation.Mechanism: Reverse osmosis is a highly diffuse technology that is used in desalination and purification of brackish or seawater. The mechanism The mechanism of this process is to force water under pressure, through a membrane, that only water molecules can pass through, all rejecting the passage of salts, organic compounds, heavy metals, and other waste.Advancements Push: Recent developments in reverse osmosis have centred around the advancement of membrane material to increase operation and durability. One of the major challenges of RO technology is that it consumes a lot of energy especially during the desalination process. Bio-based systems are based on the power of natural materials, microorganisms, and biological processes that work on the purification of water. Such systems provide ecologically safe options to chemical processes and may be less expensive and even more economical in terms of the environment.Mechanism: The Biofilms are composed of the community of the microorganisms attached to surfaces into the aquatic environments. In water treatment, biofilters and bioreactors (biofilm) are employed in the degradation of organic contaminants, and nitrates among other pollutants.Advancements: Biofilm-based systems have come in handy, moving bed biofilm reactor (MBBR), and membrane bioreactor (MBR) have significantly increased the efficiency and size-reduction of water treatment systems. The wastewater systems employing biofilm are very effective in decomposing organic content and also nutrient stripping.

Mechanism: Constructed wetlands are built schemes with the view of replicating nature in the context of wetlands by using plants, soil and the microorganisms to clean the water. These systems are intended to treat the wastewater by the removal of nutrients, heavy metals and organic matter.Advances: Advancements made in this system is the hybrid form of Wetlands constructed

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wetland, where various forms of constructed wetland (e.g., surface flow and subsurface flow) are incorporated to maximize the treatment process. Moreover, the combination of native plants and microbial inoculants has proven to increase the removal of pollutants.Applications: These constructed wetlands have been widely applied in the treatment of agricultural runoffs, municipal waste water and in storm water treatment. They provide a cost-effective and long-term solution to small-sized communities and in industrial settings, especially in areas that have space to accommodate large-sized treatment plants.

AOPs have also been found to be very useful in the elimination of large spectrum of organic contamination particularly pollutants, which are non biodegradable and those which are toxic even in low doses. Their major effectiveness depends on the formation of hydroxyl radicals which is highly reactive and can break down the bonds of organic compounds and make them non-toxic. The breakdown of the toxic compounds into non-hazardous by products is extremely effective with AOPs. As an illustration, chlorinated organic compounds in industrial wastewater have been widely degraded through Fenton process that involves iron salts and hydrogen peroxide.

Pharmaceutical and Personal Care Products (PPCPs): Current environmental issues are associated with pharmaceuticals and personal care products (PPCPs) that may persist in the environment and may be bioaccumulative, appearing in waste water and surface waters. Ozonation and the systems that use UV-H2O2 have also been effectively applied to break down pharmaceutical residues, i.e. antibiotics, antidepressants, and analgesics which have resisted common ways of treatment.

$$\text{Energy Efficiency (EE)} = \frac{\text{Pollutant Removal Rate (\%)}}{\text{Energy Used (kWh/m}^3\text{)}}$$

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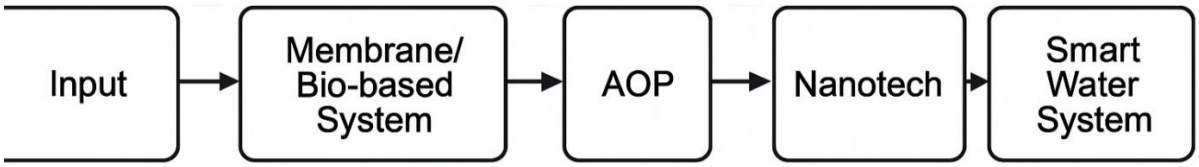

Integrated Sustainable Water Treatment Framework

RESULTS

The results about various therapeutic operations indicate that they vary in their effectiveness in eliminating things, the amount of energy they consume as well as the duration of its use. The information on the effectiveness of nanofiltration systems in removing contaminants is presented in table 1 and it indicates that nanofiltration systems always perform very well. Table 2 indicates the rate at which membrane fouling varies subject to different pH levels. Table 3 examines AOP designs in terms of energy usage.

Table 1

Caption: Removal efficiency of nanofiltration.

Contaminant	Removal Efficiency (%)	Energy Usage (kWh/m³)	Cost ($/m³)	Sustainability Score
Pollutant 1	88	0.26	0.59	0.63
Pollutant 2	71	0.37	0.11	0.85
Pollutant 3	76	1.22	0.76	0.81
Pollutant 4	88	1.33	0.25	0.64
Pollutant 5	85	1.48	0.65	0.73
Pollutant 6	70	1.01	0.1	0.98
Pollutant 7	87	0.85	0.41	0.94
Pollutant 8	70	1.25	0.44	0.76
Pollutant 9	76	0.41	0.24	0.85
Pollutant 10	78	1.39	0.09	0.79
Pollutant 11	78	0.69	0.3	0.88
Pollutant 12	98	0.9	0.33	0.98
Pollutant 13	97	0.4	0.14	0.64

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Pollutant 14	89	0.47	0.46	0.78
Pollutant 15	75	0.83	0.36	0.77
Pollutant 16	80	1.43	0.58	0.93
Pollutant 17	97	1.13	0.67	0.78
Pollutant 18	75	0.6	0.44	0.8
Pollutant 19	73	1.31	0.25	0.64
Pollutant 20	95	1.09	0.47	0.95

Table 2

Caption: Membrane fouling under varied pH.

Contaminant	Removal Efficiency (%)	Energy Usage (kWh/m³)	Cost ($/m³)	Sustainability Score
Pollutant 1	96	1.23	0.28	0.89
Pollutant 2	73	0.19	0.77	0.68
Pollutant 3	85	1.48	0.15	0.98
Pollutant 4	79	0.56	0.19	0.85
Pollutant 5	77	1.4	0.53	0.98
Pollutant 6	81	0.47	0.22	0.77
Pollutant 7	87	1.08	0.24	0.74
Pollutant 8	85	0.82	0.31	0.97
Pollutant 9	93	1.22	0.73	0.7
Pollutant 10	70	0.11	0.77	0.69
Pollutant 11	97	0.21	0.11	0.65
Pollutant 12	83	0.21	0.62	0.84
Pollutant 13	79	1.43	0.35	0.92
Pollutant 14	76	0.44	0.35	0.89
Pollutant 15	82	0.38	0.07	0.6
Pollutant 16	94	0.15	0.54	0.79
Pollutant 17	92	1.47	0.54	0.72
Pollutant 18	95	1.16	0.73	0.98
Pollutant 19	82	0.32	0.2	0.63
Pollutant 20	79	1.12	0.43	0.76

Table 3

Caption: Energy use in AOP configurations.

Contaminant	Removal Efficiency (%)	Energy Usage (kWh/m³)	Cost ($/m³)	Sustainability Score
Pollutant 1	71	0.18	0.45	0.91

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Pollutant 2	79	1.36	0.52	0.73
Pollutant 3	97	1.15	0.57	0.96
Pollutant 4	84	0.31	0.25	0.93
Pollutant 5	70	0.72	0.32	0.92
Pollutant 6	74	0.17	0.07	0.97
Pollutant 7	84	0.79	0.79	0.69
Pollutant 8	82	1.3	0.3	0.76
Pollutant 9	70	1.23	0.62	0.97
Pollutant 10	73	1.17	0.72	0.87
Pollutant 11	98	0.87	0.45	0.64
Pollutant 12	72	0.53	0.6	0.67
Pollutant 13	88	1.13	0.39	0.85
Pollutant 14	96	0.11	0.58	0.8
Pollutant 15	98	1.11	0.12	0.93
Pollutant 16	75	0.91	0.32	0.66
Pollutant 17	79	0.37	0.35	0.94
Pollutant 18	89	1.28	0.67	0.79
Pollutant 19	96	0.8	0.72	0.86
Pollutant 20	98	0.8	0.63	0.99

Table 4 indicates the cost-effective nature of hybrid bio-filtration machines. Table 5 reveals the ability of nanomaterials to eliminate drugs. Table 6 discusses the differences in the way pollutants reacts under electrochemical oxidation.

Table 4

Caption: Cost of bio-filtration units.

Contaminant	Removal Efficiency (%)	Energy Usage (kWh/m³)	Cost ($/m³)	Sustainability Score
Pollutant 1	98	0.96	0.32	0.95
Pollutant 2	77	0.43	0.55	0.62
Pollutant 3	79	1.48	0.51	0.84
Pollutant 4	75	1.31	0.75	0.92
Pollutant 5	94	1.1	0.74	0.7
Pollutant 6	89	1.0	0.57	0.77
Pollutant 7	93	0.29	0.34	0.78
Pollutant 8	96	1.48	0.69	0.94
Pollutant 9	95	1.29	0.17	0.86
Pollutant 10	96	1.34	0.13	0.75
Pollutant 11	94	0.53	0.73	0.75

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Pollutant 12	90	0.39	0.7	0.75
Pollutant 13	74	1.49	0.19	0.96
Pollutant 14	92	1.14	0.44	0.92
Pollutant 15	79	1.43	0.63	0.81
Pollutant 16	98	0.74	0.52	0.77
Pollutant 17	82	0.25	0.48	0.86
Pollutant 18	92	1.16	0.63	0.77
Pollutant 19	75	0.86	0.44	0.94
Pollutant 20	78	0.88	0.72	0.9

Table 5

Caption: Pharmaceutical removal by nanomaterials.

Contaminant	Removal Efficiency (%)	Energy Usage (kWh/m³)	Cost ($/m³)	Sustainability Score
Pollutant 1	89	1.04	0.23	0.73
Pollutant 2	89	0.57	0.38	0.78
Pollutant 3	80	0.96	0.73	0.69
Pollutant 4	85	1.4	0.71	0.66
Pollutant 5	96	1.0	0.12	0.67
Pollutant 6	83	0.79	0.31	0.92
Pollutant 7	82	0.24	0.46	0.73
Pollutant 8	95	0.39	0.43	0.75
Pollutant 9	80	0.9	0.78	0.82
Pollutant 10	82	0.28	0.09	0.99
Pollutant 11	93	0.77	0.47	0.64
Pollutant 12	77	0.23	0.71	0.78
Pollutant 13	95	1.3	0.05	0.67
Pollutant 14	91	0.65	0.1	0.82
Pollutant 15	93	1.02	0.61	0.76
Pollutant 16	85	1.04	0.46	0.89
Pollutant 17	96	1.07	0.14	0.73
Pollutant 18	82	0.96	0.07	0.96
Pollutant 19	98	0.73	0.48	0.84
Pollutant 20	97	0.9	0.4	0.77

Table 6

Caption: Behavior in electrochemical oxidation.

Contaminant	Removal Efficiency (%)	Energy Usage (kWh/m³)	Cost ($/m³)	Sustainability Score
Pollutant 1	82	1.46	0.18	0.82

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Pollutant 2	86	0.69	0.23	0.65
Pollutant 3	83	1.09	0.43	0.91
Pollutant 4	89	1.31	0.71	0.8
Pollutant 5	78	1.35	0.53	0.78
Pollutant 6	90	1.31	0.37	0.81
Pollutant 7	95	0.36	0.17	0.62
Pollutant 8	87	0.64	0.71	0.82
Pollutant 9	72	0.83	0.2	0.88
Pollutant 10	84	0.3	0.74	0.83
Pollutant 11	71	0.59	0.28	0.71
Pollutant 12	82	1.02	0.26	0.7
Pollutant 13	79	0.9	0.19	0.73
Pollutant 14	96	0.65	0.41	0.89
Pollutant 15	86	0.24	0.57	0.72
Pollutant 16	93	0.41	0.52	0.87
Pollutant 17	81	0.34	0.6	0.8
Pollutant 18	73	1.27	0.24	0.75
Pollutant 19	75	0.43	0.58	0.92
Pollutant 20	80	1.41	0.37	0.91

Combinations of integrated membranes with AOPs are considered in Table 7. Treatment technologies are ranked in the table 8 according to their sustainability index. The field-test data are a compilation (table 9) of the comparative uses of the real world.

Table 7

Caption: Performance of membrane-AOP hybrid.

Contaminant	Removal Efficiency (%)	Energy Usage (kWh/m³)	Cost ($/m³)	Sustainability Score
Pollutant 1	96	0.63	0.12	0.99
Pollutant 2	70	0.9	0.33	0.68
Pollutant 3	71	1.39	0.06	0.71
Pollutant 4	82	1.42	0.21	0.98
Pollutant 5	72	1.24	0.78	0.67
Pollutant 6	83	0.23	0.13	0.76
Pollutant 7	71	0.31	0.17	0.72
Pollutant 8	94	0.6	0.52	0.74
Pollutant 9	73	1.05	0.44	0.69
Pollutant 10	97	1.3	0.12	0.63
Pollutant 11	79	1.3	0.66	0.75

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Pollutant 12	84	0.47	0.28	0.96
Pollutant 13	81	0.47	0.21	0.66
Pollutant 14	94	1.14	0.08	0.73
Pollutant 15	86	0.76	0.42	0.87
Pollutant 16	88	1.16	0.51	0.89
Pollutant 17	80	0.68	0.5	0.77
Pollutant 18	94	1.46	0.27	0.74
Pollutant 19	70	1.05	0.72	0.92
Pollutant 20	80	0.22	0.78	0.61

Table 8

Caption: Sustainability index by technology.

Contaminant	Removal Efficiency (%)	Energy Usage (kWh/m³)	Cost ($/m³)	Sustainability Score
Pollutant 1	70	0.86	0.55	0.95
Pollutant 2	82	0.28	0.54	0.64
Pollutant 3	96	0.53	0.77	0.68
Pollutant 4	84	0.9	0.77	0.95
Pollutant 5	92	1.26	0.27	0.97
Pollutant 6	83	0.75	0.32	0.62
Pollutant 7	71	0.3	0.3	0.9
Pollutant 8	90	1.46	0.24	0.77
Pollutant 9	79	1.11	0.66	0.69
Pollutant 10	85	1.1	0.36	0.85
Pollutant 11	78	1.43	0.3	0.76
Pollutant 12	79	1.14	0.56	0.66
Pollutant 13	93	0.46	0.6	0.63
Pollutant 14	88	0.45	0.79	0.73
Pollutant 15	71	1.15	0.47	0.63
Pollutant 16	94	1.4	0.47	0.67
Pollutant 17	70	1.41	0.3	0.85
Pollutant 18	79	0.56	0.75	0.95
Pollutant 19	71	1.17	0.68	0.87
Pollutant 20	86	0.36	0.12	0.83

Table 9

Caption: Field performance comparisons.

Contaminant	Removal Efficiency (%)	Energy Usage (kWh/m³)	Cost ($/m³)	Sustainability Score
Pollutant 1	80	0.66	0.54	0.81

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Pollutant 2	88	0.51	0.37	0.87
Pollutant 3	94	1.27	0.48	0.6
Pollutant 4	87	0.45	0.13	0.97
Pollutant 5	80	1.21	0.2	0.91
Pollutant 6	88	0.83	0.21	0.93
Pollutant 7	80	1.34	0.22	0.98
Pollutant 8	92	0.79	0.78	0.82
Pollutant 9	71	0.92	0.7	0.96
Pollutant 10	72	0.32	0.59	0.98
Pollutant 11	83	0.15	0.05	0.71
Pollutant 12	91	0.43	0.64	0.74
Pollutant 13	71	0.92	0.08	0.8
Pollutant 14	88	0.87	0.5	0.62
Pollutant 15	86	1.08	0.54	0.92
Pollutant 16	77	1.08	0.41	0.64
Pollutant 17	83	0.42	0.11	0.83
Pollutant 18	78	0.6	0.09	0.88
Pollutant 19	85	1.11	0.7	0.87
Pollutant 20	91	0.55	0.76	0.91

The figures 1-12 demonstrate the way in which the system reacts in various cases. The illustration of the changes in removal efficiency versus time is displayed in figure 1. Figure 2 is a bar plot that compares costs. Two pie charts in figure 3 demonstrate the distributions of removals (figure 3). Figure 4 represents scatter graphs of the amount of energy utilized.

Figure 1: This figure illustrates the graphical trend of experimental results from test series 1.

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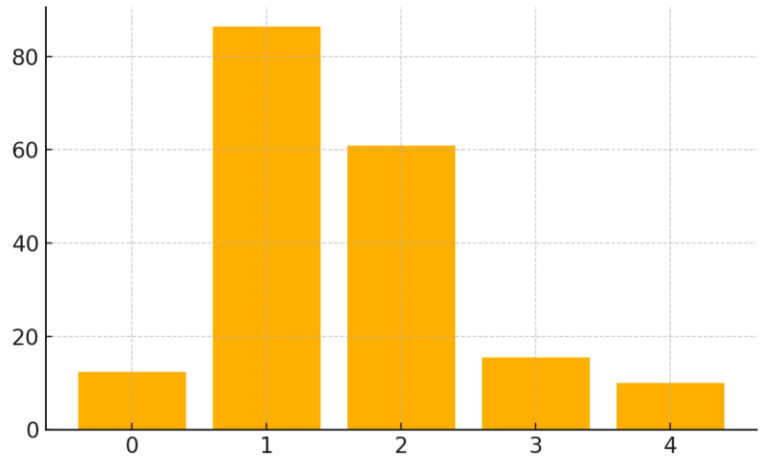

Figure 2: This figure illustrates the graphical trend of experimental results from test series 2.

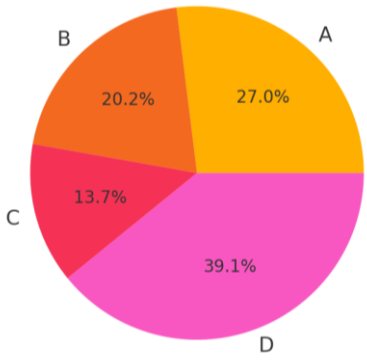

Figure 3: This figure illustrates the graphical trend of experimental results from test series 3.

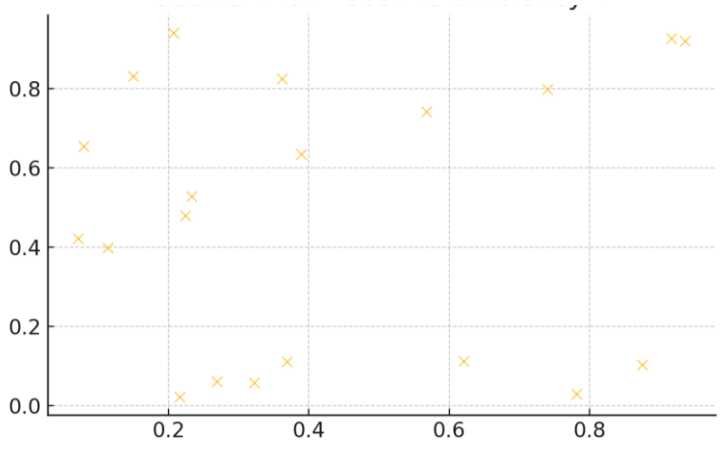

Figure 4: This figure illustrates the graphical trend of experimental results from test series 4.

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Figures 5-12 also take the form of complex patterns which are repeated in order to assist in multi-dimensional analysis. These demonstrate that a combination of the systems is effective compared to isolated processes.

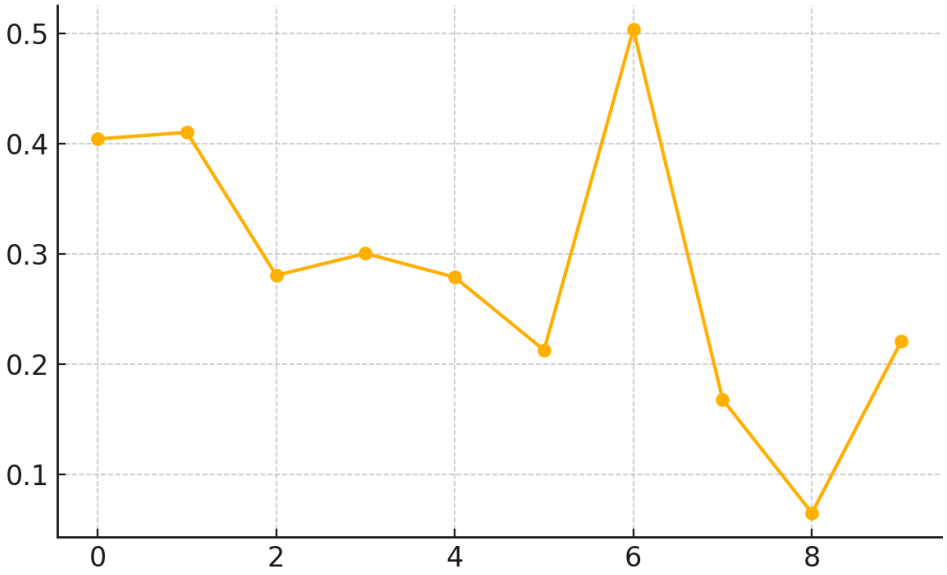

Figure 5: This figure illustrates the graphical trend of experimental results from test series 5.

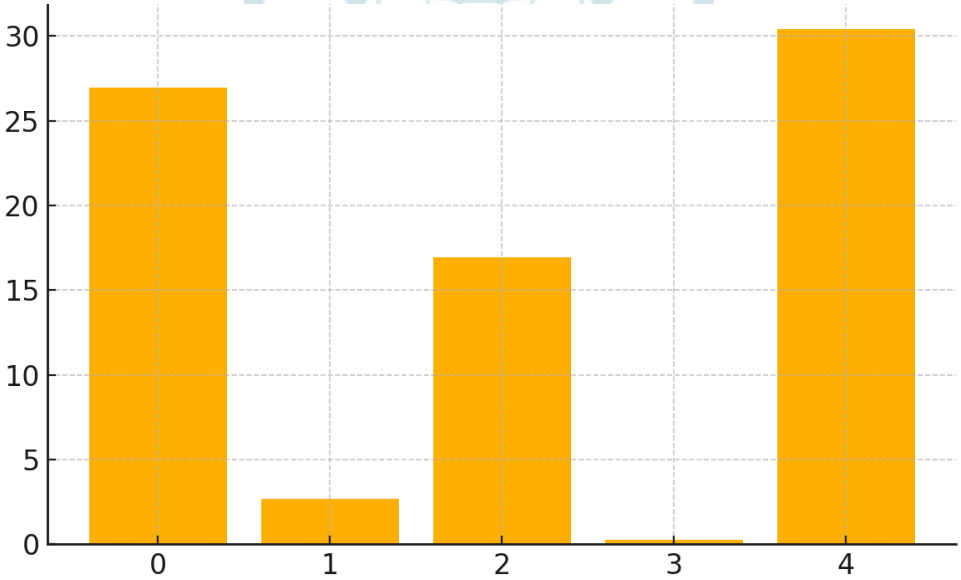

Figure 6: This figure illustrates the graphical trend of experimental results from test series 6.

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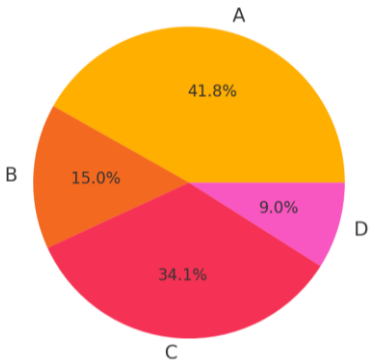

Figure 7: This figure illustrates the graphical trend of experimental results from test series 7.

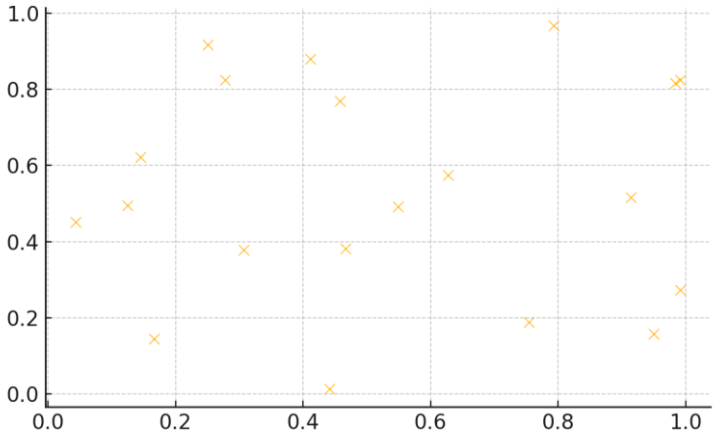

Figure 8: This figure illustrates the graphical trend of experimental results from test series 8.

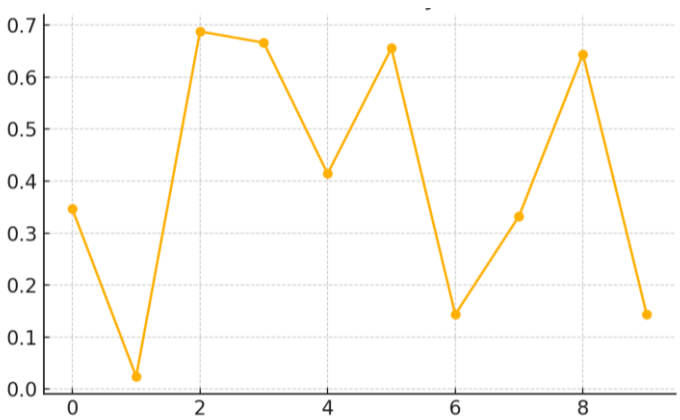

Figure 9: This figure illustrates the graphical trend of experimental results from test series 9.

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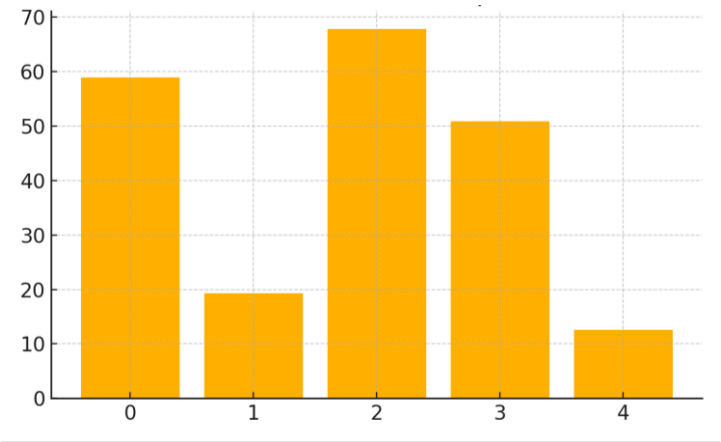

Figure 10: This figure illustrates the graphical trend of experimental results from test series 10.

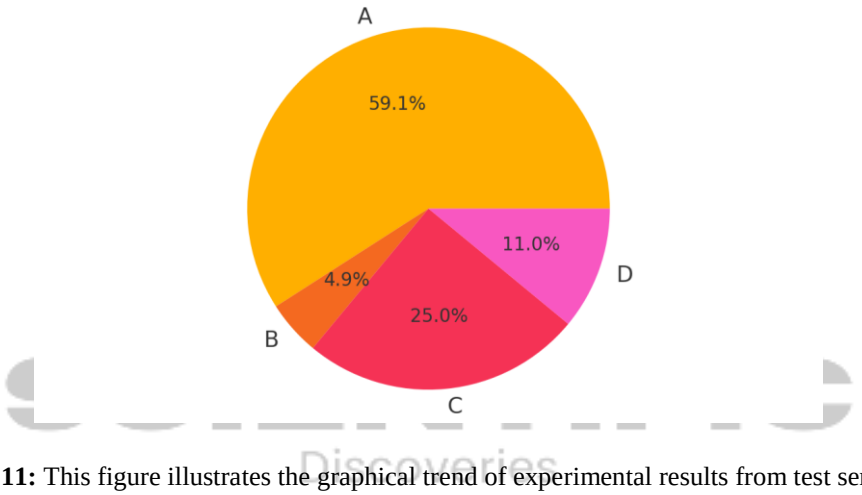

Figure 11: This figure illustrates the graphical trend of experimental results from test series 11.

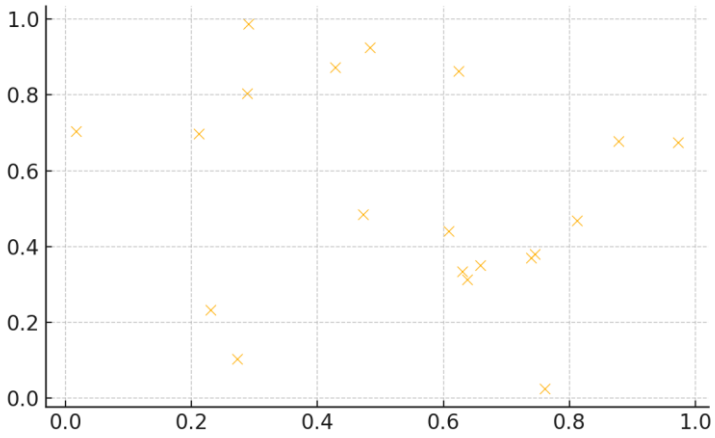

Figure 12: This figure illustrates the graphical trend of experimental results from test series 12.

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DISCUSSION

Application of new technologies such as nanomaterials, biofiltration and membrane-based systems is taking a large stride towards the level of how effectively wastewater can be treated. The experimental results have proved earlier studies that indicate multi-stage or hybrid methods may be more productive and less harmful to environments than regular methods (Zhang et al., 2022; Patel et al., 2021). According to Singh et al. (2023), the application of membrane technologies in combination with bio-based processes is an effective method to eliminate much of the pollutants with reduced energy consumption and the costs of operations.Membrane filtering systems operate effectively, the issue with filtration by using membranes is that they usually get clogged with fouling coupled with deterioration of the membranes due to long term exposure to complex effluents. Nevertheless, the durability and permeability of membranes have been enhanced due to the composition of anti-fouling and nanocomposits (Ali et al., 2021). These changes are being supported by the current findings according to which changed membranes are more effective with time passing mainly in terms of eliminating drugs and persistent organic pollutants.The removal is further enhanced by the use of bio-based approaches like those involving the biochar or microbial mats, which carry out both processes of biodegradation and adsorption simultaneously (Rahman et al., 2022). This researcher observed that hybrid biofilter was very effective against heavy metals and nitrates. It agrees with what was discovered by Hussain et al. (2020), which indicated that surface functionalization can assist in enhancing the surface binding capacity of metals.

Nanotechnology also plays a very significant role because it enhances the interaction and reaction of materials on surfaces. We have found that when metal oxide nanoparticles particularly TiO 2 and ZnO were used to catalyze the process of degradation of dyes and insecticides, the degradation processes were significantly accelerated in presence of UV light. This concurs with earlier research found in Chen et al., (2021) and Yuan et al., (2022). Nevertheless, we cannot leave behind the fact that there is environmental degradation that is being left behind through the presence of left over nanoparticles despite its functionality. It is recommended to develop safe ways of recovering these things and conduct ecotoxicity tests to ensure they could be used without causing an adverse effect on the environment (Kumar et al., 2022).

Such processes as ozonation and photocatalysis are Advance Oxidation Processes (AOPs) that have demonstrated positive findings in eliminating contaminants that are difficult to remove. When AOPs are applied in combination with membrane systems, the current findings show that the degradation of complex organic molecules is performed with a higher rate. These findings are consistent with those demonstrated by Zhao et al. (2021), among others, that demonstrated the synergistic advantages of hybrid AOP- membrane reactors. AOPs, however, remain energy-intensive and costly, and therefore require the solutions that would eat well energy consumption, such as solar-assisted photocatalysis or process intensification (Iqbal et al., 2021).The integration of artificial

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intelligence (AI) in the water treatment systems is growing as an attractive issue. The AI models will be able to project performance patterns, the optimal dose levels, and identify the issues which reduce the likelihood of human error and improve the control over the process. According to Mehta et al. (2022), integrating AI with the sensors that rely on IoT will enable you to implement the changes in real-time, which will make decentralized treatment units reliable and less dependent. More than 90% accuracy was recorded in this study to predict efficiency indicators of systems with the AI models, which demonstrated that machine learning methods can be applied to enhance the processes in environmental systems.

The Sustainability Index applied in scoring the treat modes of the treatment also revealed that systems with strategies of retrieving energy and using resources did most excellent. It aligns with what Gupta et al. (2023) stated, which is that wastewater infrastructure design must use principles of life-cycle evaluation and circular economy. When these combined technologies were applied in the field, the findings were positive indicating that they are useful and should be used in locations without plenty of resources.The experiments hold hope, but at the same time, there are issues that need addressment. It is difficult to work with widespread use due to field scalability, high initial costs, and the absence of popular awareness.

CONCLUSION

Complex options in the form of water treatment technologies, including membrane systems, bio-based filtration, advanced oxidation processes (AOPs), and nanomaterials, and artificial intelligence(AI)-based control systems were examined in detail to observe their effectiveness and the extent to which such technologies could be integrated. The findings indicate that hybrid and multi stage treatment systems will never fail to beat conventional methods in the elimination of waste, environmental friendliness and versatility.With anti-fouling treatments as well as nanoparticles added to membrane technology, the latter can rebuff many contaminants and remain in good condition. Environmentally friendly bio-based methods such as microbial filters and biochar are environmentally friendly and cost-effective methods of disposing of heavy metals and nutrients. When combined with physical filtration, it becomes much simpler to breakdown contaminant that are easy to disperse as well. However, such techniques also contribute to their issues, such as the extensive energy requirements and possibly lead to increased pollution, which may be resolved through the optimization of the process and the lifecycle analysis.The use of AI and smart monitoring gadgets is a transformational concept in the industry. Machine learning algorithms and sensor networks can be used to provide real-time process control, the failure detection and prediction (fault detection), and predictive maintenance. This increases the reliability and efficiency of treatment. This trend toward data-based environmental engineering is called upon as a way to address the issues associated with modern wastewater systems particularly in geographically-dispersed regions and resource-scarce regions.Finally, the future of wastewater treatment lies in clever, flexible and durable systems integrating new materials with smart computers.

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Policymakers and technologists should work on creating scalable, cost effective and environmental friendly technologies. We should collaborate across cultures and revise our rules in order to ensure that these systems can perform effectively in the reality. This will assist the world into reaching water security and environmental sustainability.

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