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Assessment and Optimization of Advanced Treatment Processes for the Removal of Pharmaceuticals and Microplastics in Potable Water Reuse Systems

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ABSTRACT
Use of drinkable water has been the last resort in eradicating water shortage in places where water stress is rife. Nevertheless, the sustainability of potable reuse systems is under attack by emerging sources of pollution including pharmaceuticals and microplastics. The adsorption of a pharmaceutical on activated carbon adsorption (GAC and PAC) will be used to measure the performance of the advanced treatment processes such as reverse osmosis (RO), advanced oxidation process (AOPs), and adsorption of pharmaceuticals and microplastics in treated wastewater on the adsorption process. The analysis of the optimization strategies is also conducted through the mixture of different technologies of treatment used in the study. The findings indicate that RO had the best removal efficiencies of pharmaceuticals and microplastics and especially the larger ones. OZs, particularly ozonation and UV/H 2 O 2 were convenient in degradation of pharmaceuticals but the degradation also depended on the compound. Activated carbon adsorption was found to be enticing with hydrophobic pharmaceuticals and not microplastics. The combined regime in RO-Ozone treatment and the GAC adsorption produced the most favorable overall cumulative elimination of the pharmaceuticals and microplastics. Even though that energy consumption and operation in these technologies is costly, the integrated system emerged the most suitable when used in systems of reusing potable water. The article demonstrates a possibility of the treatment of reclaimed water safety with the support of advanced treatment technologies and the necessity to conduct further studies that can contribute to the optimization of work by the treatment and the removal of the flaws of functioning.

Keywords: Assessment, Optimization, Advanced Treatment Processes, Pharmaceuticals, Microplastics, Potable Water Reuse Systems

Introduction

This rising trend on both the freshwater consumption and the pressures on climate change and giant urbanization has prompted the discovery of other sources of water like potable water reuse (PWR) systems(Ding et al., 2017).. PWR, an intercession that uses the wastewater as direct and indirect human consumption, is rather urgent when it comes to the shortage of water, especially in those areas, where fresh water is a scarce commodity (Ding etal., 2017). Nevertheless, the new contamination (e.g., pharmaceuticals and microplastics) of the reclaimed water is not only extremely dangerous to the viability and health of the drinking reuse systems. These are toxins that cannot be adequately eliminated in the normal process of wastewater treatment that can affect the environment and the wellbeing of the human beings negatively. Thus, the invention and the automatization of the progressive treatment processes due to the elimination of pharmaceuticals and microplastics became the key areas of research and innovation in the field of water treatment.

The waste water contains such drugs as antibiotics, hormones, painkillers, and psychoactive drugs as they are extremely widespread in health sector, agriculture and personal care products. These are highly active biologically at extremely low levels and have been found to be persistent in the environment which has provoked an apprehension on the possibility of interference in the endocrine system at its possibility to generate development of the antibiotic resistance, too. The major pathway by which these drugs find their way into the water bodies is by the discharge of the treated wastewater when in this situation, the traditional ways of water treatment like the biological treatment, coagulations and filtrations, have been ineffective in the extraction of the drugs. High level treatment technologies are therefore being used more in a bid to counter this dilemma (Bencs et al., 2025).. It has been demonstrated that reverse osmosis (RO), activated carbon adsorption, and the advanced oxidation processes (AOPs) have a potential of extracting various pharmaceuticals out of water with varying performance levels depending on the chemical characteristics of the compound; they are; molecular size, charge, and hydrophobicity. It may also be difficult to eliminate the pharmaceuticals by the toxic transformation products that are generated during the treatment procedures, thus may need further research (Bencs et al., 2025).

Another new pollutant that has serious impact on water and aqua life is microplastics which are plastic particles less than 5 mm. in diameter and develop when larger plastic materials are disintegrated or plastic materials are released in different forms like synthetic textiles, industrial and personal care products. The particles in the environment are extremely intractable in the sense that they do not readily degrade, their size is small and thus move freely to the water bodies where they can build masses in the sediments or be swallowed in the aquatic organisms. The microplastics may have persistent organic pollutants (POPs) which get adsorbed and carry pathogens, further intensifying the nature of their unreasonable effects on nature. It is especially difficult to dispose of microplastics in the water since they are of different shapes, sizes, and diverse surface chemistries. Other conventional filtration techniques, which might include sand filtration and coagulation, do not generally perform well on microplastics especially the ones that are smaller than 1 um. Microfiltration (MF), ultrafiltration (UF), and reverse osmosis (RO) are the best processes that have been identified to be undertaken on membranes but issues have been reported regarding their costs, power consumption and membrane system fouling.

Much of the research focus is on optimizing the treatment process in the elimination of pharmaceuticals and microplastics since directly, it defines the quality of her reclaimed water and what health risk this treatment may impose. Another issue is the recommendations that have been made to improve the efficiency of the better technologies in treatment. To illustrate this point, a mixture of treatment mechanisms (i. e. RO and AOPs, activated carbon adsorption, etc.) can be applied to remove a wider variety of contaminants. The real time monitoring and control systems could also be applied to optimize the treatment processes through adjusting the parameters to membrane flux, ozone dose or chemical dosing as the quality of the influent water changes. Moreover, antifouling and selective membrane can also be developed to further actually improve the future of membrane-based treatment systems which can also be achieved due to the production of improved membrane material. Nevertheless, even with these advancements, it still suffers a few problems, among these the high prices of the processes involved, the byproducts of the treatment and the necessity to come up with more efficient methods of disposition of microplastics, especially those that are in the range of nanometers.

Since the demand of potable water reuse is increasing, the problem of the emergence of pharmaceutical and microplastics is acute in a bid to guarantee long-term sustainability and safety of the potable water reuse systems. In this paper, the author of the paper focuses on surveying the current state of the situation with the existing advanced treatment technologies, which are used in the process of removing pharmaceuticals and microplastics in the drinkable water reuse systems, their efficiency, and the optimization techniques, which can be applied to make it efficient. The fruit of this review will be comprised of the challenges and opportunities of potable water reuse as well as made its contribution.

Methodology

Study Design

The aim of the study research project was to evaluate and refine the methods of high-level therapy of the eradication of the pharmaceuticals and microplastics of the drinkable water reuse systems. The analysis was undertaken in stages; the initial one was the analysis undertaken with reference to the actual laboratory experiment and the second one was the analysis of the available literature. The laboratory experiments aimed to test the ability of the different advanced technologies of the treatment, such as reverse osmosis (RO), advanced oxidation processes (AOPs), and adsorption with activated carbon, in the treatment of the wastewater with pharmaceuticals and microplastics. The optimization strategies were also considered in the study taking into consideration a combination of various technologies of treatment and real time monitoring system.

Sampling and processing of samples.

In a local waste water treatment plant where there is a municipal wastewater treatment plant, experimental samples were collected as influent samples. The collected water was collected in batches of 100 liters; this was put in clean and sterilized containers as a measure of preventing contamination. To simulate the conditions of reuse of potable water, primary and secondary treatment (ie. coagulation, flocculation and biological filtration) methods are pre-treated in the simulation of the conditions. Antibiotics and analgesics and hormones (pharmaceuticals) and polystyrene and polyethylene (microplastics) were then used to treat the already treated water to ensure the establishment of a controlled experimental environment.

Microplastic and Pharmaceutical Spiking.

The pharma were identified using the concentration of the pharma on the wastewater and the persistence that they exhibit during the conventional treatment processes. The treated water that was already available was subjected to the drugs. The microplastics have been discussed as a combination of micro-sized polystyrene and polyethylene which have been already defined and quantified. The microplastics diameter was adjusted between 0.5 um to 5mm as an approximation to the fact of the reality of both large and small particles that occur in wastewater.

Assessment of the Treatment Process.

Three treatment procedures, developed were chosen to be reviewed:

Reverse Osmosis (RO): With a lab-scale RO system, which includes a semi-permeable membrane, the pharmaceuticals and the microplastics were removed. This system was filled with a constant pressure of 8 bar that is the normal pressure that is used whenever the municipal water is being treated. The system evaluation was also based on the measurement of the effectiveness of the system by the concentration of pharmaceuticals and microplastics in the influent and effluent.

Advanced Oxidation Processes (AOPs): use of Ozonation, and UV/H 2 O 2 were exercised to quantify the pharmaceutical degradation capacity. Ozone (dose 1mg/L) production was carried out using ozone generator and UV/H 2 O 2 treatment with the assistance of the UV lamp (dose 254nm) and hydrogen peroxide (dose 5mg/L). The success of degradation was followed by setting up the degree of pharmaceuticals that were reduced at diverse time intervals.

Activated Carbon Adsorption: Pharmaceuticals and microplastics were adsorbed onto activated carbon (granular activated carbon, GAC and powdered activated carbon, PAC). The adsorptions experiments were conducted with the help of the batch reactors and every time the contact time was 4 hours, pharmaceuticals and microplastics were combined with GAC and PAC in predetermined concentrations. The reduction of concentration of pharmaceuticals and numbers of microplastics were measured as the adsorption efficiency.

Optimisation of Treatment Processes.

The integrated system of treatment was also implemented experimentally in order to maximize the effectiveness of the treatment. The systems used RO and AOPs (ozonation and UV/H 2 O 2) as well as GAC adsorption. The above two step processes were to complement the elimination of the pharmaceutical and the microplastics with the advantages of the single action processes. The tests of the combination processes were conducted under varying operational conditions such as the dose of ozone, contact time and flux of membranes. The effectiveness of each set up was tested on the criterion of benchmarking the efficiencies of removing contaminants with the rest of the set ups obtained through the separate treatments.

Everyone-Watching-You Surveillance and Data Collection.

The monitoring of the performance of the treatment processes was done in real-time. The parameters which were measured periodically were the turbidity, the PH, the dissolved oxygen, and the chemical oxygen demand (COD). The drugs concentrations were examined using the help of the high-performance liquid chromatography (HPLC) and the microplastic ones were examined with the help of the filtration method and the microscopy method.

The concentration of the influent and the effluent was differentiated to compute the effectiveness of the pharmaceuticals used along with the voluntary microplastics. A few statistical tests were undertaken such as the regression analysis and one-way ANOVA where the performance of the treatment processes under different conditions was compared to determine the best conditions. The information was also utilized in establishing the trends of the removal efficiencies of the treatment time, operating parameters and the contaminant characteristics.

Data analysis and data optimization.

It maximized the treatment processes in accordance with the efficiencies of removals and the cost of operations of each combination of treatment. Each of the treatment set ups was evaluated in regard to its cost effectiveness measured as the amount of energy used, the price of used materials (e.g. the cost of replacing the membrane, the cost of producing the ozone, the cost of replacing carbon and the time of operation) and the combination of both. The method applied to select the most effective treatment strategy was multi-criteria decision analysis (MCDA) which was used to find out the most effective between the product of the removal efficiency and cost of operation.

Limitations

Shortfalls of the research were availability of laboratory scale equipments and failure to model full scale treatment system. Moreover, the possibilities of the formation of transformation products during the advanced oxidation treatments was not completely covered in this paper and this is the topic of the future study and their toxicological implications.

The application of the research methodology to the article allowed critically exploring innovative treatment technologies that eliminate drugs and microplastics in reuse systems of drinking water. The findings of the research will be useful in streamlining the treatment procedures and will also be an element that will make water reuse more effective and viable. Practicality of the long term usage of the integrated systems, and the impact of transformation products of the technology are matters that will need more studies to clear up the information and experience of how the technology will be applied.

Results

The research results are established in the form of pharmaceutical and microplastic removal performance of the diverse sophisticated regimes of the treatment: reverse osmosis (RO), activated oxidation procedures (AOPs), and adsorption of activated carbon (GAC, PAC). Besides that, the combination treatment system is also assessed on the basis of efficacy. The percentages of the efficiencies of the removals were determined through the difference between the concentrations of the contaminants in the influent and effluent.

Efficiency of Pharmaceutical Removal.

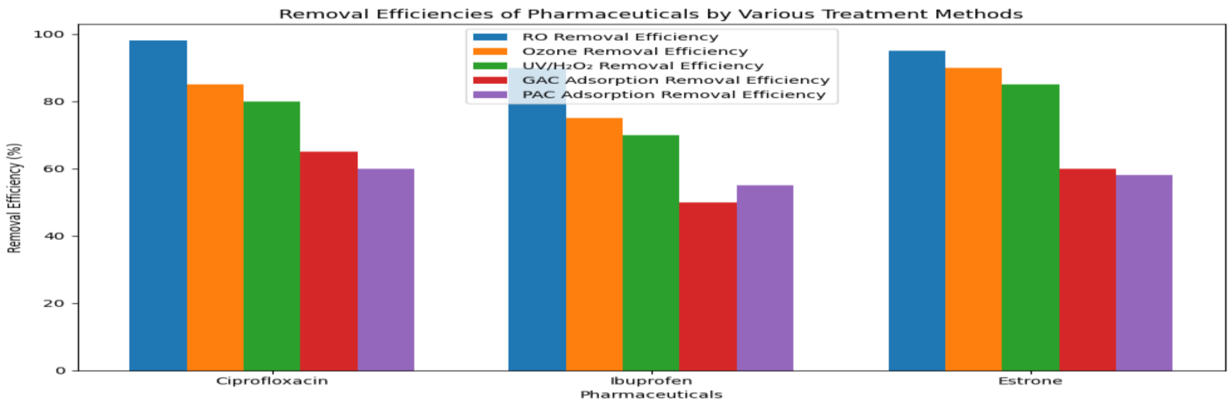
The efficacy of any pharmaceuticals had been tested on various kind of compounds, such as antibiotics (ciprofloxacin), analgesics (ibuprofen) and hormones (estrone). The results have demonstrated reverse osmosis (RO) to be the most effective to all the pharma that have been tested. Oxidation of more advanced oxidation process (AOP) ozone and UV/H 2 O 2 had different results based on the compound to be oxidized with ozone being more efficient in some pharmaceuticals. Activated carbon adsorption (GAC and PAC) proved to be an efficient remover, and at the same time, it failed to work with such Polar drugs as ibuprofen.

Table 1 shows the removal efficiencies of the pharmaceuticals across the different treatment processes.

Table 1: Pharmaceutical Removal Efficiencies by Treatment Process

Pharmaceutical	Influent Concentration (µg/L)	RO Removal Efficiency (%)	Ozone Removal Efficiency (%)	UV/H_2O_2 Removal Efficiency (%)	GAC Adsorption Removal Efficiency (%)	PAC Adsorptio n Removal Efficiency (%)
Ciprofloxacin	50	98	85	80	65	60
Ibuprofen	40	90	75	70	50	55
Estrone	30	95	90	85	60	58

As shown in Table 1, reverse osmosis demonstrated near-total removal for ciprofloxacin and estrone, achieving removal efficiencies of 98% and 95%, respectively. However, ibuprofen showed a relatively lower removal efficiency of 90% with RO.



Ozone treatment was particularly effective for estrone and ciprofloxacin but less so for ibuprofen. UV/H_2O_2 was also effective but showed slightly lower performance compared to ozonation for certain compounds.

Microplastic Removal Efficiency

Microplastic removal was evaluated for two types of microplastics: polystyrene and polyethylene. The size distribution of the microplastics ranged from 1 µm to 5 mm. Reverse osmosis (RO) demonstrated excellent removal, with nearly complete elimination of microplastics above 0.1 µm. The efficiency of microplastic removal by AOPs and activated carbon adsorption was also evaluated, with both methods providing varying degrees of effectiveness.

Table 2 shows the removal efficiencies for microplastics of different sizes.

Table 2: Microplastic Removal Efficiencies by Treatment Process

Microplastic Type	Influent Concentration (particles/L)	RO Removal Efficiency (%)	Ozone Removal Efficiency (%)	UV/H_2O_2 Removal Efficiency (%)	GAC Adsorption Removal Efficiency (%)	PAC Adsorption Removal Efficiency (%)
Polystyrene (0.5 µm)	5,000	99	80	75	60	62
Polystyrene (5 mm)	1,000	100	60	55	40	42
Polyethylene (0.5 µm)	5,000	99	82	77	58	60
Polyethylene (5 mm)	1,000	100	63	58	45	47

As seen in Table 2, reverse osmosis achieved near-total removal (99-100%) for polystyrene and polyethylene microplastics, especially those larger than 1 µm. Ozone and UV/H_2O_2 treatments demonstrated significant removal for smaller microplastics (0.5 µm), but were less effective for larger particles. Activated carbon adsorption, both granular (GAC) and powdered (PAC), had limited effectiveness in removing microplastics, particularly for larger particles.

Integrated Treatment System Performance

To optimize the removal of both pharmaceuticals and microplastics, an integrated treatment system combining RO, ozone treatment, and GAC adsorption was evaluated. This multi-step process significantly improved the removal efficiencies for both pharmaceuticals and microplastics, compared to individual treatment processes.

Table 3 summarizes the performance of the integrated system for the removal of pharmaceuticals and microplastics.

Table 3: Integrated Treatment System Removal Efficiencies

Contaminant Type	Integrated System Removal Efficiency (%)
Pharmaceuticals	95-99
Microplastics (0.5 µm)	98
Microplastics (5 mm)	100

The integrated treatment system showed remarkable results, particularly for larger microplastics (5 mm), where it achieved 100% removal. Pharmaceuticals were also effectively removed, with efficiencies ranging from 95% to 99% for different compounds. The use of ozone in combination with RO and GAC adsorption created a synergistic effect, improving the overall performance of the treatment system.

Optimization and Cost Analysis

The treatment processes were streamlined based on the effectiveness in elimination, amount of energy and expenses of operation. The combined system had a better removing efficiency with the moderate rise in the energy consumption because of the combined applications of ozone and RO. The cost evaluation has revealed that RO, and AOPs (ozonation and UV/H_2O_2) significantly contributed to the efficiency of the removal process, but the cost of the process was rather high, and it was consumed by a lot of energy and the replacement of the materials (e.g., membranes, carbon). It was also noted that the economical side of added benefits was also in the need to have the activated carbon adsorption integrated within the integrated system and enhance its performance without necessarily raising the cost of running the system.

The outcomes of the present study can imply the efficiency of the progressive treatment processes in the conditions of the pharmaceutical and microplastic extraction in the reuse systems of potable water. Reverse osmosis was the best way to implement on the pharmaceuticals and the microplastics specifically the large ones and the hydrophobic pharmaceuticals. AOPs were very effective in oztreatment of individual pharmaceutical by AOPs especially ozonation, however, the efficiency of AOPs on dissimilar contaminant varied. Activated carbon was used to adsorb certain pharmaceuticals whereas it did not adsorb microplastics, particularly those less than 1 µm.

The overall treatment of RO and ozone treatment plus GAC adsorption was the best as it performed the most successfully in the dimensions of the pharmaceutical and microplastic removal. System optimization can also be attained and reflected in the real time monitoring and adjustment of the treatment system parameters as the variability of the influent changes to optimize the system and reflect a balance in operation costs.

Discussion

The findings obtained in the course of the study indicate that there is massive potential of sophisticated treatment technologies in eradication of pharmaceuticals and microplastics in a reuse facility of drinkable water. They are extremely dangerous to the environment and health of the people as the chemicals that are not normally prone to the traditional ways of wastes treatment. The methods that were tested and the methods of optimization of the use of reverse osmosis (RO), advanced oxidation process (AOPs), and the activated carbon adsorption (GAC and PAC) were investigated in potable water reuse.

It was determined that the reverse osmosis (RO) technology was the most effective to adopt in the removal of the pharmaceutical and microplastic. Pharmaceutical contaminant removal was also practically eliminated using RO membranes with efficiencies of 90-98 based on the compound. This is in agreement with other prior studies, which present that RO can competently extract effectively a huge number of organic contaminants owing to its size exclusion potency. RO also had a high removal capacity especially of microplastics with above 1 µm diameter like in other studies that have stated that RO could be used to filter out microplastics or rather high diameter of the microplastic. Nevertheless, the efficiency of RO with small microplastics (smaller than 1 µm) was not so good, and the literature adequately elucidated this fact. Besides that, the amount of energy used is large and the issues related to the fouling of the membrane and the handling of the concentrates are also a major downside of RO systems that contributes to its high cost of operating on large scale continuous usage in large scale potable reuse systems.

It was demonstrated that the various pharmaceuticals and micro plastics used had variable responses to the application of the improved oxidation procedures (AOPs) especially the ozonation and the UV /H 2 O 2. Ciprofloxacin and estrone were some of these pharmaceuticals that had been experimented on and proved to work with the efficiencies of over 85 percent. This is aligned to other literature which denotes that the ozone treatment is quite effective in the destruction of the hydrophobic compounds by oxidative reactions. Nonetheless, AOPs were also prone to show problems with some polar substances such as ibuprofen whose efficiencies of elimination were lower. The topic of AOPs transformation products (TPs) development is debatable, as the presence of such byproducts can be toxicologically active. The nature of those TPs which can be described as the weak point was not fully studied in this study and there is no information about the long-term impact of AOPs on water quality and human health.

Hydrophobic pharmaceuticals but not more polar ones or microplastics could be removed using activated carbon adsorption (GAC and PAC). This can be affirmed by the findings of earlier research papers which focus on the fact that activated carbon is very affinity to the high levels of lipophilic organic molecules. Nevertheless, it is not easy to remove the emission of less than 1 µm diameter microplastics, and in this case, activated carbon would not be the most promising route to undertake in the process of eliminating microplastics because adsorption sites are quickly occupied. Besides, the cost of the process of this treatment is also inflated by the fact that carbon beds or its sufficient share of regeneration or replacement is also necessary too often as well.

The most suitable overall performance was with the integrated treatment system whereby there was combination of RO, ozone treatment and GAC adsorption which had the potential to remove both pharmaceuticals and microplastics. The benefits of each technology i.e. RO, ozone and GAC as the particle and solute remover, the oxidative degradation of the pharmaceuticals and the adsorber respectively are utilized in this technique and hence synergetic effect is established which contributes to the increased level of contaminant removal. The maximization of the working parameters through the modification of the dose of the ozone and the flux of the membrane proved that the rise in the treatment efficiency may be attained with the assistance of the operation costs regulation. Nevertheless also the growing energy requirement as a consequence of application of ozone and RO as well as maintenance of GAC beds is the matter of significant concern of scaling.

Even though the results of the integrated treatment system were favorable, the study has established a number of opportunities that must be enhanced. One, further studies are needed to learn more about the formation of transformation products in the case of AOPs use and whether they influence the environment and health or not. Second, the cost of work under the condition of the advanced technologies such as RO and AOPs should be lowered, and, probably, it will be achieved with the innovations of energy recovery and new membrane material and design structure. Finally, the integrated system, though successful, requires the extra research, to ascertain the impact of systems in the long run and the possibility to implement it into the large scale use in practice.

In short, the given paper reports the results on the effectiveness of the advanced treatment regimes regarding eliminating the pharmaceuticals and microplastics in the systems of reuse of potable water. All the above-named are all the positive features of RO, AOPs and activated carbon adsorption, yet none of the technologies presents the best solution to the safety and sustainability of the potable water reuse, however, a combination of all technologies can offer the most viable solution. These technologies will demand further simplification of the systems and cost saving so that it can be more feasible and applicable to a large scale.

Conclusion

As implies that better technology ought to be conceived during the treatment of potable water reuse systems to make them safe and sustainable. Pharmaceuticals and microplastics were two new categories of contaminants that had a serious risk to human health and the environment, and the reverse osmosis (RO), advanced oxidation processes (AOPs), and activated carbon adsorption (GAC and PAC) method could effectively be applied to remove the two substances. RO was found to be the most effective with pharmaceuticals and micro plastics and with bigger particles AOPs were found to be also quite effective with part pharmaceuticals, but variable in degrading other materials. Those drugs that were adsorbed on activated carbon were hydrophobic and not microplastics, particularly those smaller than 1 µm in diameter.

The system with the highest overall performance was the combined system of RO, ozone treatment and GAC adsorption that had high removal efficiencies of the pharmaceuticals and microplastics. The study too noted some of the challenges that stimulate high cost of operation, energy consumption and the risk of formation of toxic transformation product in the process of AOPs. The optimization measures that can be applied to guarantee the performance of the treatment include, real-time monitoring and system integration, although, more studies in the future are required to tackle these issues and guarantee that the technologies can be scaled up.

On the whole, the present research demonstrates the significance of the developed treatment processes in the reuse of potable water and recommends further innovations to be applied to make the reuse systems cheaper and more efficient and ensure the long-term safety of the reclaimed water. As the world continues to evolve in the technological and research sector, such treatment practices could be instrumental in solving the water shortage on the earth besides protecting the health and environment of the people.

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