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Occurrence, Risks, and Treatment of Pharmaceutical Contaminants in Malaysia's Aquatic Systems

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ABSTRACT: Pharmaceutical and personal care products (PPCPs) are increasingly recognized as emerging contaminants in aquatic ecosystems due to their persistence, bioaccumulation potential, and adverse effects on both human health and aquatic life. In Malaysia, particularly in the state of Selangor, the rapid growth in population and healthcare demand has led to rising pharmaceutical consumption and subsequent contamination of surface water, tap water, and drinking water sources. Recent studies have detected compounds such as diclofenac, triclosan, ciprofloxacin, caffeine, and sulfamethoxazole in local water bodies, with concentrations often exceeding those reported in developed countries such as Australia and Taiwan. This trend highlights the inefficiency of conventional wastewater treatment plants (WWTPs) in removing pharmaceutical residues. The persistence of these contaminants poses potential health risks, including antibiotic resistance, endocrine disruption, and long-term toxicity to aquatic organisms and humans. Current treatment technologies in Malaysia, including adsorption, bioremediation, and activated sludge systems, have shown partial removal efficiency but remain inadequate for complete elimination of PPCPs. To address this limitation, emerging research recommends integrating hybrid treatment systems that combine biological and physicochemical processes to enhance contaminant removal efficiency. The aim of this study is to assess the occurrence and distribution of pharmaceutical contaminants in Selangor's aquatic system, evaluate their potential risks, and discuss the limitations of existing wastewater treatment technologies while proposing sustainable alternatives for improved water quality management. Overall, the findings emphasize the urgent need for policy revision, technological innovation, and stricter monitoring to safeguard public health and environmental integrity in Malaysia.

KEYWORDS: Pharmaceutical contaminants; drinking water quality; hybrid wastewater treatment; environmental and public health

1. Introduction

PPCPs are considered and referred to as emerging contaminants, which come in diverse groups and can be detected in various environments such as water bodies, soils, sediments, and even biota [1−2]. Although pharmaceuticals have helped to improve public health through modern medicine, the increase in number of cases regarding water pollution caused by pharmaceutical residues has raised global awareness. PPCPs are known for the high potential of bioaccumulation and ecotoxicity, meaning that the compounds found in PPCPs accumulate in an aquatic environment as well as posing harmful threat to the aquatic organisms and the public health [3−4]. PPCPs can disrupt ecosystems, alter the activities, impair reproduction and development of invertebrates, fishes, and even humans through the rapid growth of bacteria that are resistant towards antibiotics [1].

In Malaysia, Selangor has one of the highest population densities and healthcare service demands. The total utilization of medicine continues to show an increasing trend from 2011 to 2022 alongside the increase in population, with a small 0.4% decrease in the year 2021 [5−8]. The data is recorded in the Malaysian Statistics on Medicine (MSOM), presented in Table 1 and Figure 1. The number of population are consuming medicines and using personal care products like cosmetics continue to increase, therefore making PPCPs a major contributor to pollution [9]. Rapid urbanization and inadequate wastewater infrastructure also play a role in the presence of pharmaceuticals in surface and drinking water sources. High concentrations of pharmaceutical residues are commonly found in water bodies around residential disposal areas and it can enter various aquatic environments, which include discharge from sewerage treatment plants (STPs), agricultural and stormwater runoff, and improper disposal that ultimately leads to the contamination of drinking water sources [10].

Table 1. Medicine utilization in malaysia (2011–2022).

Year	Utilization (Define daily dose/1000 inhabitants/day)	% Increase
2011	433.47	NA
2012	514.08	15.7
2013	553.51	7.1
2014	569.55	2.8
2015	624.90	8.9
2016	632.32	1.2
2017	717.85	11.9
2018	821.45	12.6
2019	862.91	4.8
2020	927.39	7
2021	923.58	-0.4
2022	955.31	3.3

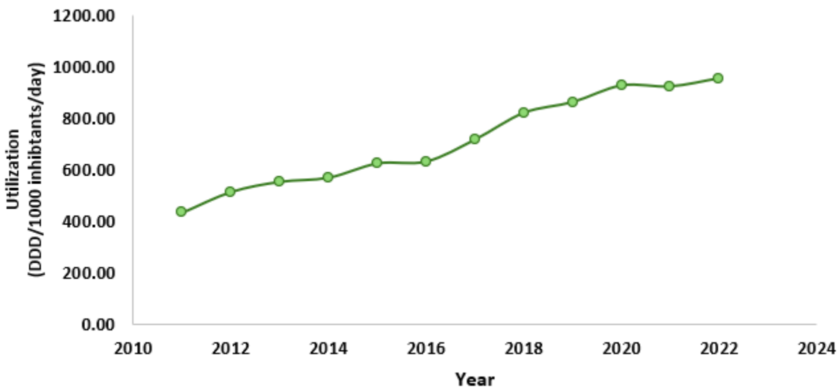

Figure 1. Increasing trend of pharmaceutical consumption in malaysia over 11 years.

This essay aims to explore the source and occurrence of pharmaceuticals in the rivers, tap water (TW), and drinking water (DW) of Selangor, as well as the potential risk it poses towards the river ecosystem and public health. It also addresses the major challenge which is the incomplete removal of pharmaceuticals by conventional wastewater treatment plant (WWTPs), limited public awareness of proper disposal, and the absence of specific regulations addressing PPCP pollution.

2. Sources and Occurrence of Pharmaceuticals in Rivers, TW, and DW

Recent study reported an increase in concentrations of various pharmaceuticals that bear potential risks to human health such as caffeine, ciprofloxacin, amoxicillin, diclofenac, sulfamethoxazole, and triclosan in Selangor DW [11]. These pharmaceuticals were recorded to be the most used or consumed medication in healthcare institutions across Malaysia [5]. The increasing concentration of pharmaceuticals alongside other contaminants in Selangor Rivers resulted in Class III category in Water Quality Index [12]. This implies that there has been widespread occurrence and distribution of pharmaceutical waste residues across urban and rural areas. The major pharmaceuticals identified in Malaysian water bodies are summarized in Table 2.

Table 2. Common pharmaceutical compounds found in water bodies with usage.

Category	Compounds	Usage (change to hazards – human & marine ecosystem)	References
Antibiotics	Ciprofloxacin	Treat bacterial infections, chest infections, skin and bone infections	[13]
	Penicillin	Treat bacterial infections for humans and animals, including venereal diseases	[14]
	Sulphonamide	Treat diuresis, hypoglycemia, thyroiditis, inflammation, and glaucoma, as well as the main compound to various groups of drugs like Sulfamethazine and Sulfadiazine	[15]
	Triclosan	Used in antiseptic, treat skin infection	[16]
Stimulant	Caffeine ($C_8H_{10}N_4O_2$)	Stimulant and psychoactive substance	[17]
Analgesics & Antipyretics	Paracetamol / Acetaminophen	Treat mild to moderate fever and acute pain	[18]
NSAID	Ibuprofen Diclofenac	Anti-inflammatory and pain relief, treat fever, symptoms of arthritis, headaches, muscle pain, menstrual pain	[19]
Diuretic medicine	Furosemide	Make kidney produce more urine, treat Edema due to heart failure or kidney disease	[20]
Contraception & Hormones	Norethindrone	Prevent pregnancy, treat endometriosis	[21]
	Ethinyl estradiol	Prevent pregnancy, synthetic estrogen	[22]

The primary reason that pharmaceuticals emerge as contaminants is the improper disposal practices and the design of WWTPs that is not specifically engineered to remove them [23]. A survey was conducted on public awareness about the impacts of pharmaceutical waste on health and environment. The result reported that about 80% of the respondents acknowledge the risks pharmaceuticals pose, however it also showed a contrast in practical application of disposal method, where respondents throw unused and expired medication in household garbage with relatively high percentage of 47.4% and 84.9% respectively [24]. Another study was conducted on the disposal methods of pharmaceutical wastes and the results showed that 2.9% of the households pour the wastes down the drain, 8.8% pour down the sink, and 2.9% flush it down the toilet [9]. Although the percentages might seem insignificant, this behavior introduces the pharmaceutical residues into the urban water cycle [25]. This cycle consists of 4 main elements: influent that mainly comes from municipal wastewater discharge, STPs effluents, the surface water containing those effluents, and distributed water utilized or consumed by the community after treated by water treatment plants (WTPs) [26]. The urban water cycle is illustrated in Figure 2.

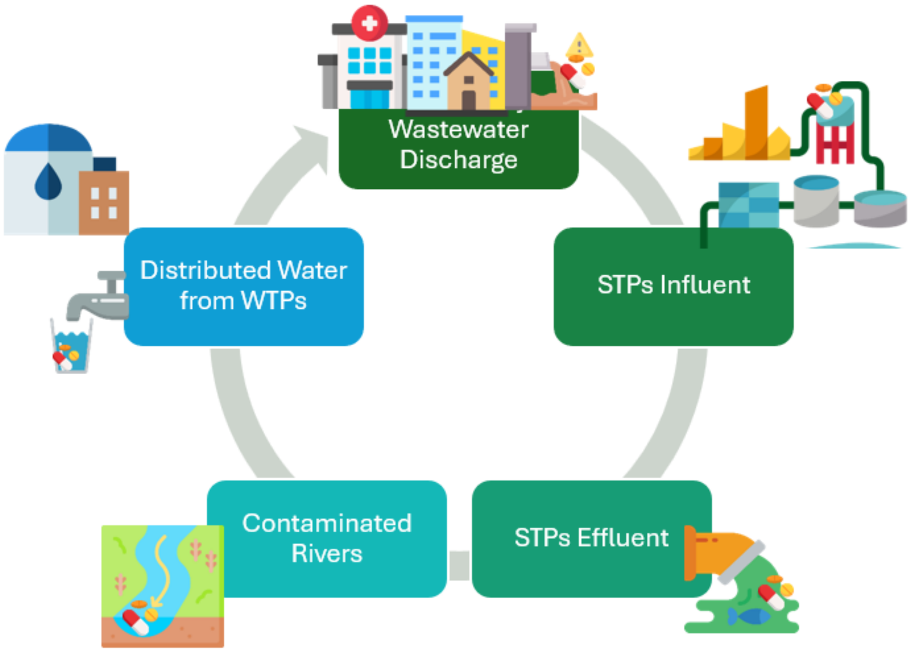

Figure 2. Pharmaceuticals in urban water cycle without proper treatment.

Since most of the detected pharmaceuticals come from municipal wastewater discharges, STPs play an important role in completely removing or ensuring safe concentration of pharmaceuticals in their discharged effluent [27, 28]. Currently, the conventional water treatment technologies in Malaysia are highly ineffective at completely removing pharmaceuticals, which directly affects the river water. However, other contaminants from municipal or industrial wastewater besides pharmaceuticals are also present in STPs influent. Sometimes the pharmaceutical residues can be made more toxic when treated together alongside other harmful contaminants, posing health risks for the public and river ecosystem, especially if the river is used as TW or DW source [29−30].

3. Reported Concentration of Pharmaceuticals in Rivers, TW, and DW.

In TW, the concentration ranges from 1.93 ng/l of ciprofloxacin to 130 ng/l of ethinyl estradiol [31, 32]. This implies that residues containing hormonal compounds might consistently be in the cycle even to the point of consumption. Lower contamination levels were recorded in Kajang DW with 0.67 ng/l ciprofloxacin, 0.23 ng/l sulfamethoxazole, and 0.05 ng/L diclofenac [11]. Samples in Putrajaya showed similar low concentrations with caffeine and triclosan being the most noticeable at 0.38 ng/l and 0.36 ng/l respectively [33]. River water samples are reported to have concerningly higher concentrations, which highlights removal inefficiency and contamination from WWTPs effluents. Klang River has a high concentration of caffeine at 20.62 ng/l, but Gombak River is higher with 36.53 ng/l [34−36]. Gombak River contained an average of 262.53 ng/l ciprofloxacin and 103.08 ng/l sulfamethoxazole, meanwhile Langat River contained extremely high levels of norethindrone and diclofenac at 7135 ng/l and 112.7 ng/L respectively [27, 32, 36]. The findings are summarized in Table 3. Overall, the data represents concerning trend where concentrations of pharmaceuticals are significantly higher in river systems than in treated water, reflecting the incapability of WWTPs in completely removing these emerging contaminants.

A comparison was done to rivers, TW, and DW in some developed countries including Spain, Australia, and Taiwan. Results showed that pharmaceutical concentrations in Selangor water are higher compared to other countries. For instance, ciprofloxacin in Gombak River is around 262.53 ng/l and it exceeds the detected concentration in Madrid and Australian rivers at 112.75 ng/l and 1.3 ng/l respectively. 103.08 ng/l of sulfamethoxazole was detected in Gombak River, meanwhile 456.5 ng/L in Madrid and only 1.0 ng/l in Australian rivers [36−39]. In Australia, the detected concentrations in TW reduce significantly to non-detected in DW, showcasing their advanced WWTP systems [38]. In TW and DW particularly, Selangor showed concerningly high concentrations of pharmaceuticals compared to Australia and Taiwan, where advanced technologies are already integrated into WWTP and DW systems (Table 3).

Table 3. Pharmaceutical contaminants concentration in TW and DW.

Location	Pharmaceutical	Average Concentration (ng/l)	References
Selangor TW	Diclofenac	6.46	[31]
	Triclosan	2.57	
	Ciprofloxacin	1.93	
	Caffeine	2.39	
	Ethinyl estradiol	130	[32]
Kajang DW	Ciprofloxacin	0.67	[11,35]
	Sulfamethoxazole	0.23	
	Triclosan	0.12	
	Diclofenac	0.05	
	Caffeine	0.08	
Putrajaya DW	Caffeine	0.38	[33]
	Triclosan	0.36	
	Ciprofloxacin	0.32	
	Diclofenac	0.14	
Klang River	Caffeine	20.62	[34]
Gombak River	Ciprofloxacin	262.53	[36]
	Caffeine	36.53	
	Diclofenac	15.07	
	Sulfamethoxazole	103.08	
Langat River	Diclofenac	112.7	[27]
	Furosemide	104.4	
	Acetaminophen	72.4	
	Norethindrone	7135	[32]
Madrid Rivers	Ciprofloxacin	112.75	[37]
	Sulfamethoxazole	456.5	
	Caffeine	1573.5	
Madrid TW	Caffeine	35.4	
Australian Rivers	Ciprofloxacin	1.3	[38]
	Sulfamethoxazole	1.0	
Taiwan TW	Caffeine	13	[40]
	Sulfamethoxazole	2	
	Acetaminophen	3	
	Triclosan	14	
Taiwan DW	Caffeine	10	
	Sulfamethoxazole	2	
	Triclosan	8	

Despite pharmaceutical contaminants being a growing issue in Malaysia, this issue receives limited attention from the current legislative, legal framework and regulations namely the Environmental Quality Act 1974 (EQA). This continuously increases health risks to human and marine organisms. A study explained that pharmaceuticals is categorized as Scheduled Waste, where it requires to be properly treated and disposed by a licensed facility that strictly follows the EQA 1974 regulations. However, the legislation did not explicitly classify pharmaceutical residues as a parameter that must be treated in WWTPs. This paper also discussed that the regulations mostly cover industrial effluents without including pharmaceutical waste from domestic sources like households. It also concluded that although the EQA emphasizes the importance of audits and reporting of hazardous discharge, there is still a lack of documentation on pharmaceutical contaminants [39].

4. Environmental and Health Impacts

The pharmaceuticals detected in Selangor's river systems and drinking water (DW) present a broad spectrum of ecological and human health risks. Although these compounds may appear at low concentrations that do not exert immediate toxic effects, elevated levels can significantly disrupt aquatic ecosystems and pose serious threats to public health. The major environmental and physiological impacts of the key pharmaceuticals identified in this study are summarized in Table 4. Diclofenac, which is widely consumed by both humans and animals, was consistently detected across several rivers in Selangor. Experimental evidence shows that diclofenac concentrations ranging from 0.001 to 10 mg/L can impair fish fertility and reduce egg hatching success [41]. At higher concentrations, it increases chronic toxicity in aquatic environments [42] and damages vital organs such as fish gills, kidneys, and liver [43]. In humans, excessive diclofenac exposure has been linked to digestive tract injury, renal impairment, and disturbances in cardiovascular and nervous system functions [44].

Triclosan exhibits heightened toxicity when it interacts with other pollutants, altering its bioavailability and amplifying its ecological effects [45]. It has been shown to cause DNA damage, behavioral abnormalities, altered sex ratios, and embryonic deformities in aquatic organisms due to endocrine disruption [46, 47]. Human exposure is also concerning, as triclosan has been detected in blood, breast milk, and urine [16]. Toxic levels can disrupt endocrine function and increase carcinogenic risks, particularly breast cancer [16]. Ciprofloxacin poses one of the most pressing risks due to its contribution to antimicrobial resistance (AMR). Persistent environmental exposure enables pathogens to develop resistance, compromising the efficacy of antibiotics for both humans and animals [23, 48]. As highlighted by WHO, this elevates the risks associated with infection treatments and complicates procedures such as caesarean sections and chemotherapy [49]. Caffeine, although commonly perceived as low-risk, acts as a psychoactive compound affecting behavioral responses in both humans and aquatic species [17, 50]. In humans, excessive exposure may disrupt endocrine and cardiovascular functions and is particularly hazardous to vulnerable groups such as pregnant women and individuals with heart conditions [51]. Aquatic organisms exposed to caffeine may experience infertility, impaired development, neurotoxicity, metabolic disturbances, and cellular damage [50]. Ethinyl estradiol (EE2), a synthetic estrogen, is known to significantly disrupt reproductive and immune systems in fish and humans [52]. A whole-lake experiment demonstrated that concentrations as low as 5–6 ng/l can feminize male fish and potentially trigger population collapse [53], underscoring its potency as an endocrine-disrupting compound.

Sulfamethoxazole also contributes to AMR development and induces genotoxic effects that alter microbial communities within river ecosystems [54−55]. Its persistence allows resistant strains to spread into treated and drinking water systems, ultimately reducing the effectiveness of medical therapies [56]. Furosemide, a widely used diuretic, causes oxidative stress, abnormal cardiac activity, and behavioral changes in fish while inhibiting population growth [57−58]. At elevated levels in humans, furosemide may lead to electrolyte imbalances, gastrointestinal disruption, and heightened risk of complications among individuals with pre-existing health conditions [59]. Although acetaminophen is generally considered to have low ecotoxicity, degradation products from its breakdown such as aromatic and acidic metabolites, can induce harmful effects including DNA damage, cell membrane oxidation, and protein denaturation in aquatic organisms and potentially humans [60]. Norethindrone, frequently used in contraceptives and hormonal therapies, poses substantial endocrine-disrupting effects. Studies have shown that it can impair thyroid and reproductive systems in fish and amphibians [61] and, unlike EE2, tends to induce masculinization and alter swimming behavior [62]. In humans, norethindrone exposure may disrupt hormonal balance and reproductive processes [63].

Table 4. Environmental and human health impacts of selected pharmaceuticals.

Pharmaceutical	Environmental Impacts	Human Health Impacts	References
Diclofenac	• Disrupts fertility and egg hatching in fish (0.001–10 mg/L). • Causes chronic toxicity in river water. • Damages fish gills, kidney, and liver.	• Injures digestive organs (intestines). • Causes kidney damage. • Affects cardiovascular and nervous systems.	[41−44]
Triclosan	• Increases toxicity when interacting with other pollutants. • Causes DNA damage, behavioral and physical abnormalities. • Alters sex ratios; embryo deformation via endocrine disruption.	• Detected in blood, breast milk, urine. • Disrupts endocrine system; potential carcinogenicity. • Increases breast cancer risk.	[16, 45−47]
Ciprofloxacin	• Drives antimicrobial resistance (AMR) in aquatic organisms.	• AMR makes infections harder to treat. • Increases risks during medical procedures (c-section, chemotherapy).	[23, 48−49]
Caffeine	• Alters behavior in aquatic organisms. • Causes infertility, development disruption, neurotoxicity. • Changes metabolism and damages cells.	• Alters psychological behavior. • Affects endocrine and cardiovascular systems. • Higher risk for pregnant/lactating women, children, and cardiac patients.	[50, 51]
Ethinyl Estradiol (EE2)	• Disrupts reproductive and immune systems in fish. • Causes feminization of male fish.	• Affects human reproductive and immune systems.	[52−53]
Sulfamethoxazole	• Causes AMR and genotoxicity. • Alters microbiomes in river systems. • Resistance spreads to treated water.	• Increases population-level resistance to medication.	[54−56]
Furosemide	• Causes oxidative stress, abnormal heart rate, and behavior changes in fish. • Inhibits population growth.	• Leads to electrolyte imbalance. • Causes gastrointestinal and metabolic disruption.	[57−59]
Acetaminophen	• Degrades into harmful aromatic and acidic metabolites. • Damages DNA; causes cell membrane oxidation and protein denaturation.	• Exposure to metabolites can cause DNA and cellular damage.	[60]
Norethindrone	• Disrupts thyroid endocrine and reproductive systems in fish/amphibians. • Causes masculinization and behavioral changes (swimming).	• Disrupts human hormonal and reproductive systems.	[61−63]

5. Current Treatment Approaches

5.1. Bioremediation.

Bioremediation relies on microbial degradation of pollutants into simpler or non-toxic compounds, which is commonly effective for organic pollutants [64]. A study was done by utilizing a type of fungus called *Ganoderma lucidum* that is found in Malaysia and it reported a 100% decrease in level of diclofenac in synthetic wastewater, from around 600 µg/l to about 100 µg/l over 96 hours of treatment [65]. Similar study was done using the same fungus to treat urban wastewater samples containing pharmaceuticals and the result showed 100% removal ciprofloxacin, 95% sulfamethoxazole, and 37.33% diclofenac [66]. Bioremediation is a good treatment option because it is low cost and environmentally friendly, however, the overall effectiveness needs to be further studied since WWTP influents does not only contain pharmaceuticals but also other pollutants [67]. Furthermore, it is time consuming and sensitive towards environmental conditions, like temperature and humidity.

5.2. Adsorption.

Adsorption methods (physical and chemical) are popular due to the ability of different adsorbent groups to provide sites on its surface area for the binding of various pollutants [68]. A review article covered the percentage removal efficiencies and maximum adsorption capacity of 7 adsorbent groups including carbon-based (~84.34%), plant biomass-based (~74.52%), clay & clay minerals (~77.46%), silica-based (NA), zeolite-based (~80%), polymers & resin (~96.4%), as well as hybrid adsorbents (~88.72%) [68]. Although many adsorbents perform well in removing pharmaceuticals, it still face some challenges. As summary, that carbon-based materials are effective but expensive to produce, biomass-based materials are cheaper but lower surface area and stability, silica-based adsorbents cannot handle alkaline conditions [69]. Overall, further studies are required to develop more durable, affordable, and functional adsorbents.

5.3. Activated sludge treatment.

Activated sludge treatment utilizes aerobic microorganisms and adsorption to sludge [70]. It is commonly used in Malaysian WWTPs; however, it is not designed for removal of persistent pollutants not pharmaceuticals. A comparison was done to other studies. In UK, chemical coagulation/flocculation following an activated sludge treatment was able to remove 90% of ciprofloxacin, where other WWTPs only can 51% [23]. In Japan, this treatment has 75% diclofenac removal efficiency due to the adsorption into sludge [43]. With further research and studies, activated sludge treatment has high potential in removing pharmaceuticals in WWTP effluents.

6. Proposed Technology for Removal

A study showed promising method for removing various pharmaceuticals from STP effluent through membrane filtration, where 2 commercial membranes (NFX and GC) were used and the results presented that NFC was able to remove over 80% of the chosen pharmaceuticals, meanwhile GC has bigger range of removal around 10-90% [65]. This offers a variety of effectiveness in removing pharmaceutical pollutants, which can be a good option for WWTPs. Recently, another effective solution was introduced to wastewater treatment in the form of hybrid systems that combine physical, chemical, and biological treatments. Some PPCPs can be highly resistant and difficult to break down [68]. Integrating processes like membrane filtration and advanced oxidation (AOP) can give better results because AOP can oxidize non-biodegradable and toxic compounds into harmless compounds, therefore this system can both degrade and separate stubborn pharmaceutical pollutants [71].

According to a survey in Selangor, there are about 80.2% of respondents that has high awareness of water quality, but only 31.2% expressed their confidence about DW safety [72]. This shows that increasing public awareness and community engagement on pharmaceutical waste disposal is important in preventing DW contamination. This can be done through educational campaigns, frequent monitoring, advertising, and involving local pharmacies and clinics to provide safe disposal tools. Policy and regulations also play an important role in ensuring safe water quality. An amendment on the current EQA framework should be done, where pharmaceuticals are categorized as parameters that should be inspected, monitored, and reported [73].

Considering the continuous increase in pharmaceutical consumptions, population density, and environmental factors that change the bioavailability and mobility of pollutants, current traditional methods in WWTP are no longer sufficient. Implementing hybrid systems in Malaysia would significantly improve the removal of pharmaceuticals in WWTPs. The proposed technology can help reduce surface water contamination, protecting health of public and aquatic ecosystems, and ensure safety in TW and DW. The system can adapt to local wastewater characteristics and compatibility with current facilities, which makes it a practical and sustainable improvement to Malaysia's WWTP framework.

7. Conclusion

Pharmaceutical contamination in Selangor's rivers, TW, and DW emphasize the limited awareness and knowledge on treating this emerging contaminant in Malaysia. The high detection levels of various pharmaceuticals including antibiotics, hormones, stimulants, NSAIDs, analgesics & antipyretics, and diuretics in Selangor water compared to other countries imply that the current traditional WWTP systems are insufficient in eliminating the contaminants. Bioremediation and adsorption show benefits environmentally and financially but some challenges due to environmental factors still require further studies and work. The activated sludge process is commonly implemented in Malaysia; however, it is only successful in removing organics and nutrients not pharmaceuticals. Hybrid treatment technologies are proposed, specifically combining membrane filtration and AOP to completely degrade and separate complex pharmaceutical compounds. This system can be applied to existing WWTP systems to enhance practicality and scalability to Malaysia's growing population and wastewater characteristics. Additionally, this system must be enforced by amended policy frameworks, safe pharmaceutical disposal programs, and public campaigns to prevent pharmaceutical residues from entering the water cycle. In conclusion, ensuring clean and safe water in Selangor requires technological innovation, regulation amendments, and community participation to not only protect the aquatic ecosystems, but also to support public health and sustainable water management.

Competing Interest

The authors declare that they have no competing interests.

Author Contribution

Edita Ayoka Kiranparahita: Conceptualization, methodology, formal analysis, writing original draft. Nur Afiqah Rahman: Validation, writing review and editing. John Mwangi: Writing review and editing.

Data Availability

All data supporting the findings of this study are included within the manuscript. No additional datasets were generated or analyzed.

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