ScienceDirect

Process Safety and Environmental Protection
Volume 161, May 2022, Pages 392-408

Biodegradation factors and kinetic studies of point-of-use water treatment membrane in soil

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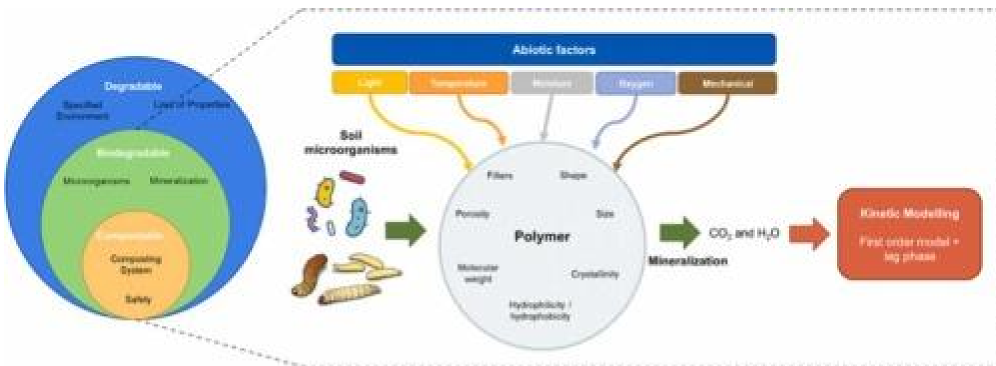
Abstract

Point-of-use (POU) water treatment technology in developing countries and rural regions is more feasible than a centralized water treatment system due to the high cost of pipe distribution. The water filtration system can provide quick and easy access to water with low maintenance and higher pathogen removal among POU technologies. However, non-biodegradable polymeric materials for water filtration membranes raise environmental concerns due to their problematic disposal. There is increasing research on biodegradable membrane material, but the validation of biodegradability is still lacking as measuring weight loss does not guarantee the complete mineralization of biodegradable membrane. This review aims to discuss various abiotic and biotic factors affecting polymer degradability in soil or compost, gather and evaluate existing studies on biodegradable filtration membrane and identify existing methods used to validate membrane biodegradability. Different kinetic models used to understand the biodegradation mechanism at different stages were studied. Factors affecting morphology and surface properties affect biodegradability. Membrane biodegradation follows a first-order model followed by a lag phase. Finally, future studies of biodegradable filtration membrane could include CO_2 quantification and phytotoxicity studies, exploring different additives and membrane formulations to balance membrane performance and degradation ability, and lastly, conducting LCA and TEA to assess overall sustainability.

Graphical Abstract



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Introduction

Water is a vital resource to sustain life on earth. Despite being covered with 71% water, the planet faces one of the most critical challenges of the 21st Century – water scarcity. Surface water and groundwater sources are diminishing due to rapid population growth, urbanization, industrialization, and climate change (Newton, 2016). Pollutants like chemicals, nutrients, and potentially toxic elements from households, commercial, and industrial wastewater and agricultural runoff make the situation worse as it is often carried away into water streams when not treated or managed correctly. Developed countries and urban areas have access to treated water, managed by centralized water treatment. However, this is not feasible in developing countries and rural areas as low-density houses significantly increase the piping and distribution costs (Pooi and Ng, 2018). Although O&M costs can be covered through government subsidies or revenues from the village committee, this is often not sustainable (Liang and Yue, 2021, Piasecki, 2019). Furthermore, no financial plan or initiatives that potentially attract private investors (Liang and Yue, 2021). Another main challenge that is often overlooked is the problem with governance in water management (Liang and Yue, 2021, Piasecki, 2019). Village committees do not manage the system efficiently, and their limited awareness and lack of participation can hinder the smooth governance of the water management system (Liang and Yue, 2021). Not to mention, technical difficulty can also pose a great challenge to building a suitable water treatment system in the area (Liang and Yue, 2021). As a result, point-of-use (POU) technology is more feasible to access water quickly and prevent water recontamination from fetching water (Pooi and Ng, 2018). Thus, there is an even more pressing need for low-cost and efficient POU water treatment technology. Membrane filtration technology is widely used for water treatment as it is easy to operate, requires less floor space, and has lower operating and maintenance costs (Chen et al., 2010). It can be used in a wide range of applications. This includes treating industrial wastewater before discharged and producing potable water from different water sources like surface water, groundwater, brackish water, or seawater. Most membranes to date are made up of synthetic polymeric materials like cellulose acetate (CA), cellulose nitrates, polysulfone, polyethersulfone (PES), polyacrylonitrile (PAN), polyvinylidene fluoride, polypropylene (PP), polytetrafluoroethylene, polyimide and nylon 6 (Chen et al., 2010, Lee et al., 2016). Despite having good mechanical strength, chemical/thermal stability, and oxidation/pH resistance, these materials are derived from non-renewable sources and are non–biodegradable. The global market demand for filtration membranes is projected to have a compound annual growth rate of 6.4% from 2019 to 2025 (MarketsandMarkets, 2019). Increasing demand contributes to fossil fuel depletion and cumulative waste generation. Therefore, this called for a more sustainable approach in formulating filtration membranes, particularly by using biodegradable materials. Some of the more commonly studied biodegradable membrane materials are polylactic acid (PLA), polycaprolactones (PCL), polybutylene succinate (PBS), polyhydroxy-alkanoate (PHA), starch, cellulose, and chitosan (Avérous and Pollet, 2012). Biodegradability is subjective as it is a natural process that can occur very slowly, from months to hundreds of years, depending on each material and the disposal environment (Rudnik, 2019, Ayilara et al., 2020, Greene, 2014). Although these materials are claimed to be biodegradable, there is not much information regarding their biodegradability under the actual environment after disposal.

The occurrence of polymer in the environment is vital pollution considering the volume of polymers used and disposed of daily, the difficulty and time required to remove it (Lambert et al., 2013). As polymers are left in the environment, several abiotic factors including light, temperature, moisture, oxygen, and mechanical stress can cause the breakage of bonds within the polymer molecules, leading to the loss of their original properties, including the molecular weight, mechanical strength, shape, size, and color (degradation) (Lambert et al., 2013). Although the fragmentation of polymers may facilitate biodegradation, the formation of microplastics (<5 mm) is problematic as they can be transported through many pathways in the environment, leading to transboundary pollution (Alfonso et al., 2021). Although soils were identified as one of the main long-term sinks for microplastics, their presence in soil received much less attention than most studies on the marine environment (Lambert et al., 2013, Rochman, 2018, Wang et al., 2020). Microplastic's hydrophobic nature can lead to changes in soil structure which may affect soil fertility (Guo et al., 2020, Du et al., 2021). Polymer residual from degradation can also have toxic effects on plant germination and growth (Chen et al., 2021). Furthermore, polymers or microplastics do not end up in the ocean before first passing through the soil, groundwater, run off to the river and ocean (Alfonso et al., 2021).

Membrane technology tends to experience performance decline due to fouling over time. Consequently, membranes had to be replaced from time to time and caused the disposal of thousands of tons of membranes every year (García-Pacheco et al., 2015). Although the end-of-life of the membrane is generally handled according to the laws of each country, currently, landfilling is the most common membrane disposal method as it is simple and cheap (Landaburu-Aguirre et al., 2016, Lawler et al., 2015, García-Pacheco et al., 2015). However, in poorly managed landfills in terms of the collection, treatment, and transport of waste, the waste can be carried away by the wind, drains, river, and run-off when the landfill is in an unsecured location or overfilled (Moqbel et al., 2019, Verster and Bouwman, 2020, Moora and Piirsalu, 2016). As a result, the waste can be deposited into sinks such as soil, river sediments and eventually carried into the ocean (Verster and Bouwman, 2020). Moora and Piirsalu (2016) reported that an estimated 4% of the marine litter in the Baltic Sea originates from dumpsites or landfills.

Furthermore, low-income countries commonly practice open dumping due to low budgets and lack of trained workforce (Ali et al., 2014). Since open dumping is not regulated, chemicals, potentially toxic elements, and other contaminants percolate into the soil and end up in water held in the soil or underground water (Ali et al., 2014). Consequently, this affects soil stability, strength, and fertility which causes physiological disorder and retards plant growth. Sharma et al. (2018) also reported some level of contamination at the upper layer of dump-yard soil. Therefore, to improve safe drinking water accessibility in rural areas, it is essential to extend the study beyond the degradability of a polymer and include its biodegradability in soil, where it is often the primary source before being transported elsewhere. In this way, the used membranes can be disposed of within the location to reduce the energy required to transport the waste to landfills and prevent unwanted transboundary pollution.

However, there are very few studies on the biodegradation of water filtration membrane after its application in an actual environment. Therefore, this review aims to discuss the different factors of polymer degradation, compare studies concerning the biodegradability of the membrane in soil or compost and study the kinetic models used in understanding the mechanism of biodegradation to help design an optimum environment for the most effective way of biodegradation. Finally, this paper will also provide recommendations for the future work of biodegradable membranes.

Section snippets

Degradation of polymer

Degradability is an important precursor process that facilitates the activity of the microorganism during biodegradation (Lambert et al., 2013). Many abiotic factors like light, temperature, moisture, oxygen and various chemicals can lead to degradation. However, most studies were performed in the laboratory using conditions not attainable in the natural environment. Some examples include chemically pre-treating high-density polyethylene (HDPE) by immersing into $KMnO_4$/HCl for 8 h and 10% of…

Biodegradation of polymer

Technically, all polymers are degradable, but not all are biodegradable or even compostable. ASTM standard D-5488 and European Norm EN 13432 define biodegradability as “capable of undergoing decomposition into carbon dioxide, methane, water, inorganic compounds (mineralization) and biomass” (Avérous and Pollet, 2012) and composting as an “autothermic and thermophilic biological decomposition of organic waste in the presence of oxygen and under controlled conditions by the action of micro and…

Biodegradability and compostability standards

Biodegradable materials are established by fulfilling two essential standards: biodegradation specification performance and biodegradation testing method. The typical standard specifications used for biodegradable plastic include ASTM D6400, ISO 17088, EN 14995, and AS 4736,which are very similar (Greene, 2014, Rudnik, 2019). Each standard contains specifications for biodegradation, disintegration, and safety. Criteria for these aspects need to be fulfilled for the polymer to be certified as…

Performance and biodegradability of existing biodegradable membranes

Based on Scopus, the number of studies on the biodegradable membrane for treating water increased by 73.5% in the past ten years. In these studies, the biodegradable polymer is always used with another biodegradable or non-biodegradable polymer of different properties to form a membrane composite. There are also cases where additives like starch, dextran, sorbitol, and PEG are added to the formulation. Different polymers and additives contribute to forming membranes with improved mechanical…

Mechanism and kinetics of membrane biodegradation in soil

The rate of polymer biodegradation in the soil is a complex phenomenon influenced by various factors simultaneously. Studying biodegradation kinetics through mathematical modeling becomes a great tool to understand the mechanism in greater detail, which helps to decide the optimum conditions or the most effective way to allow the process to take place and in the design of facilities to improve the process. In addition, mathematical modeling can also extrapolate the time required for complete…

Challenges and recommendation

People are becoming more aware of the global challenges of polymer waste management. There is also an increasing number of research on green and sustainable materials to address this problem, including water filtration membrane, which has an increasing demand. There are many studies on the biodegradable membrane, but a common shortfall is that despite claiming the membrane to be biodegradable, biodegradability studies were not conducted to validate the claim. Based on the literature review in …

Conclusion

To meet the target of the United Nations SDG 6: Clean water and sanitation for all, POU water treatment technology in developing countries and rural areas must be enforced and encouraged. Membrane filtration is one technology that requires low maintenance and provides easy access to water with high pathogen removal efficiency. However, with concerns of the conventional synthetic polymer membranes during waste management, the biodegradable membrane has become an emerging field to solve this…

Funding

This research was funded by Monash University Malaysia-ASEAN Sustainable Development Research Grant Scheme, grant number ASEAN-2019–02-PHA.…

Author contribution statement

Dora Lawrencia: Conceptualization, Methodology, Data curation, Visualization, Writing – original draft. **Lay Hong Chuah:** Funding acquisition, Writing – review & editing. **Phatchani Srikhumsuk:** Writing – review & editing. **Poh Phaik Eong:** Supervision, Visualization, Writing – review & editing.…

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.…

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