REVIEW OF LITERATURE

2. REVIEW OF LITERATURE

This literature survey provides an in-depth exploration of innovative and emerging techniques in wastewater treatment and environmental management. The first section focuses on nutrient recycling from source-separated urine, examining various methods such as nitrification, distillation, forward osmosis, microbial electrochemical processes, and alkaline dehydration. These techniques showcase the potential for efficient nutrient recovery, with ongoing research addressing challenges related to scalability and optimization.

The second section examines the use of polymers in wastewater treatment, with a particular emphasis on bio-based polymeric materials and their applications. This includes the integration of biopolymers such as chitosan, cellulose, and keratin, as well as advanced materials like polymer microspheres. The discussion highlights the advantages, challenges, and future directions for enhancing the efficacy and scalability of these materials.

In the third section, the degradation of polymers in aquatic and marine environments is reviewed. Studies on various polymers, including polyurethanes, polyethylene, polyhydroxyalkanoates, and polylactic acid, shed light on the complex interplay of physical, chemical, and biological factors that influence degradation. This section emphasizes the importance of understanding degradation mechanisms to mitigate environmental impacts. The fourth section delves into passive wastewater treatment, focusing on time-dependent passive chemical dosing systems, high-throughput sewage treatment processes, and synthetic fabric filters. These methods present sustainable solutions for wastewater management, with an emphasis on adaptability and efficiency in various operational contexts.

The fifth section examines the utilization of superabsorbent polymers (SAPs) for moisture absorption, specifically in air dehumidification and building materials. This includes the development of polymer-molecular sieve composites, superporous gels, and SAP-integrated plasters, showcasing their potential for passive humidity control and improved indoor air quality.

The final section discusses the removal of organic metabolites through the use of polymers, highlighting advanced adsorbent materials such as Hypersol-Macronet polymers, β-cyclodextrin polymers, and amide naphthotube-crosslinked polymers. These

materials exhibit considerable improvements in adsorption efficiency and regeneration capabilities, with ongoing research aimed at optimizing performance and scalability. This extensive survey is intended to provide a comprehensive overview of the current advancements and future directions in wastewater treatment and environmental management, emphasizing the significance of innovative materials and methods in addressing global challenges.
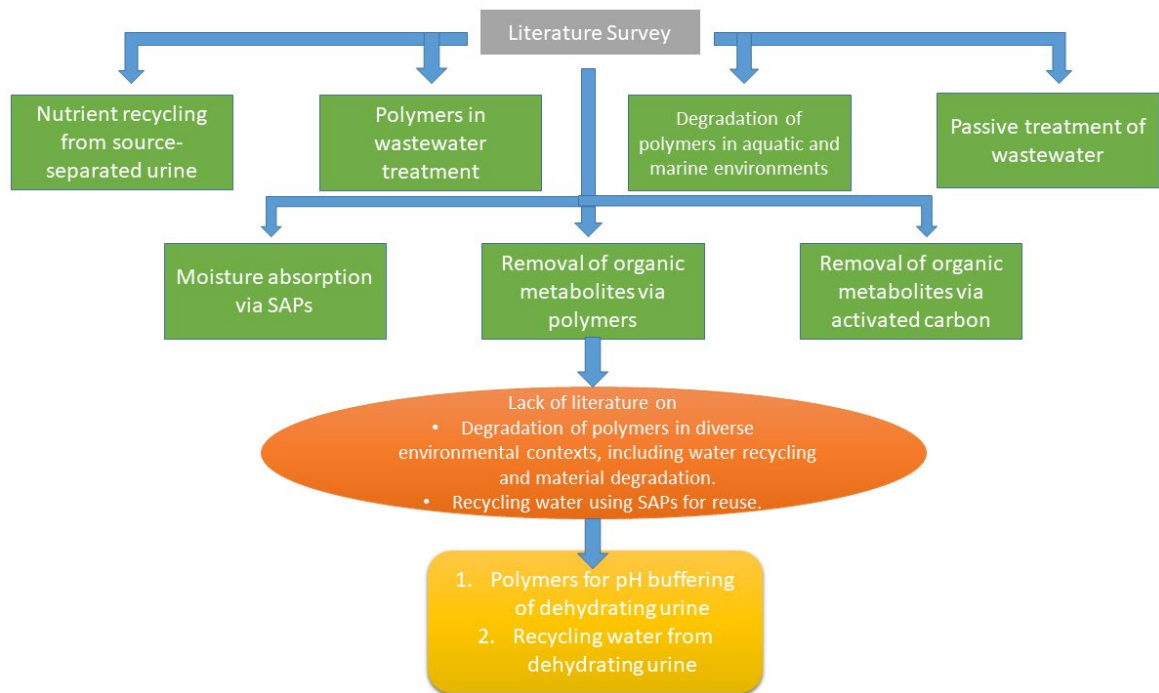

Figure 4: *Structure of the literature survey (green), existing research gap (orange) and how the objectives of the thesis aims to bridge the existing gaps (yellow).*

2.1. NUTRIENT RECYCLING FROM SOURCE-SEPARATED URINE

Udert and Wächter (Udert & Wächter, 2012) outlined a comprehensive method that combined nitrification and distillation for nutrient recovery from source-separated urine. In their study, a membrane-aerated biofilm reactor was operated stably for 12 months, resulting in the production of a nutrient solution with optimal pH and ammonium-to-nitrate ratios. This process successfully recovered all nutrients in a dry powder form, with minimal ammonia loss. By integrating reverse osmosis and vapour compression distillation, the energy demand was reduced to levels comparable to conventional wastewater treatment. Although this method demonstrates the potential for high-

efficiency nutrient recovery, scalability and energy optimization remain critical factors for broader application.

Zhang et al. (Zhang et al., 2014) investigated the use of forward osmosis (FO) dewatering to recover nitrogen, potassium, and phosphorus from source-separated urine. The FO process achieved high water fluxes and substantial rejection rates for phosphate and potassium, but the rejection of organic nitrogen was lower in fresh urine. The study found that membrane fouling and urine pre-treatment significantly impacted the efficiency of the FO process. Despite these challenges, the high nutrient recovery rates indicate that forward osmosis is a viable technique for nutrient mining, with ongoing research needed to enhance membrane performance and reduce fouling.
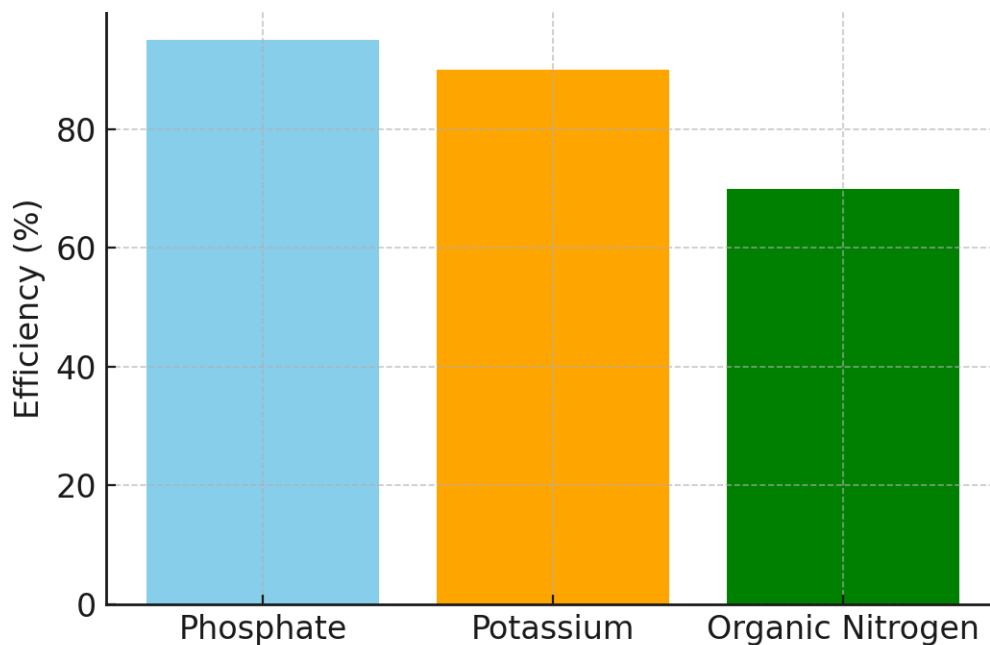

Figure 5: Nutrient recovery efficiencies of forward osmosis (FO) for phosphate, potassium, and organic nitrogen from source-separated urine.

Chen et al. (Chen et al., 2017) explored the use of a microbial electrochemical process to accelerate urea hydrolysis, facilitating efficient recovery of nitrogen and phosphorus. This wastewater-driven process significantly enhanced urea hydrolysis, achieving nutrient recovery rates of 76-87% for nitrogen and 72-93% for phosphorus. The electrical potential generated during wastewater treatment was the driving force behind the accelerated hydrolysis. This innovative approach shows promise for high-efficiency

nutrient recovery, although further work is required to optimize the process and ensure its scalability for industrial applications.

Freguia et al. (Freguia et al., 2019) created a self-sustaining bioelectrochemical system to transform human urine into a plant fertilizer. The system effectively concentrated nitrogen and potassium, and it remained stable for two months. The resulting product was free of harmful substances and met the standards of hydroponic and horticultural fertilizers. Although this innovative system offers a promising solution for nutrient recycling, its long-term viability and cost-effectiveness require further investigation.

Kabdaşlı and Tünay (Kabdaşlı & Tünay, 2018) conducted an extensive review of methods for recovering nutrients from human urine, focusing on struvite precipitation, ion exchange, and adsorption processes. They evaluated the theoretical foundations, operational parameters, efficiencies, and environmental impacts of these techniques. The study also discussed the potential for integrating emerging technologies like electrochemical and biological methods to improve nutrient recovery efficiency. The authors emphasized the need for continuous research to refine these techniques and develop cost-effective and environmentally responsible solutions.

Simha et al. (Simha et al., 2020) investigated the potential of alkaline dehydration to concentrate human urine into a nutrient-rich solid. The process successfully concentrated the urine 48 times, recovering over 90% of the nitrogen while minimizing urea degradation. The resulting product contained high levels of essential nutrients, making it suitable for agricultural use. This method demonstrates the potential for efficient nutrient recovery and concentration, but further research is needed to optimize the dehydration conditions and address potential ammonia volatilization issues.

Tao et al. (Tao et al., 2019) proposed a three-stage treatment process for recovering nitrogen and phosphorus from human urine, which involved hydrolysis, precipitation, and vacuum stripping. The study found that acetic acid could prevent scaling in urine-diverting toilets, and complete urea hydrolysis could be achieved within 20 hours at a temperature of 25°C. The addition of magnesium facilitated struvite precipitation, effectively removing phosphate, while vacuum stripping recovered ammonia as ammonium sulfate. This multi-faceted approach highlights the potential for comprehensive nutrient recovery, with ongoing research needed to optimize each stage for maximum efficiency.

Viskari et al. (Viskari et al., 2018) evaluated the use of source-separated human urine as a fertilizer for barley cultivation. The study found that urine was as effective as mineral fertilizer in terms of barley yield, with no significant differences in grain or straw yield. Additionally, no accumulation of pharmaceuticals or hormones was detected in the barley grains, highlighting the safety and efficacy of using urine as a fertilizer.

Vinnerås (Vinnerås, 2002) reviewed methods for recycling nutrients from separated urine and faeces, including thermal composting and chemical disinfection using urea or peracetic acid. The study demonstrated significant energy savings and reduced reliance on mineral fertilizers through nutrient recycling, with effective pathogen inactivation achieved by adding urea to separated faecal matter.

Ganesapillai et al. (Ganesapillai et al., 2021) demonstrated the use of industrial coal fly ash for recovering nitrogen and phosphorus from human urine. The study showed that high inlet urine concentration and minimal adsorbent loading resulted in maximum struvite precipitation for phosphorus recovery. The efficiency of the fly ash adsorption process was confirmed through kinetic modelling, indicating its potential for effective nutrient recovery from urine.

Table 1: *Summary of some urine treatment technologies to recycle nutrients* (Larsen et al., 2021).

Technology	Methodology	Key Findings	Advantages	Disadvantages
Biological Stabilization	Utilizes nitrification to stabilize urine by converting ammonium to nitrate and reducing pH.	Achieved nitrification rates of 0.5–2.5 g $N \cdot m^{-2} \cdot d^{-1}$ for biofilm reactors. Stable partial nitrification achieved over 12 months in pilot studies.	Low chemical and energy demand; reduces pH effectively.	Instability in high-salt urine; not suitable for volume reduction.
Chemical Stabilization	Employs acids or bases to inhibit urea hydrolysis and prevent pH increases.	Alkaline stabilization using $Ca(OH)_2$ maintains pH > 11, ensuring urease inhibition and phosphate precipitation.	Simple, cost-effective for alkaline stabilization; promotes pathogen inactivation.	Acid usage can be hazardous; carbonation can destabilize pH.

Electrochemical Processes	Uses electrolysis to oxidize organic matter and stabilize urine by generating oxidants like chlorine or hydroxyl radicals.	COD removal rates of 421 g $COD \cdot m^{-2} \cdot d^{-1}$ observed on boron-doped diamond electrodes (BDD); energy demand was 55 $kWh \cdot kg\ COD^{-1}$.	Effective organic matter removal; potential for energy recovery (e.g., microbial fuel cells).	High energy consumption; risk of hazardous by-products.
Drying and Distillation	Relies on evaporation to concentrate nutrients and recover water.	Drying achieved >80% nitrogen recovery at 35°C with solid fertilizer containing 7.8% N, 2.5% P, and 10.9% K (w/w). Distillation energy demand: ~110 $Wh \cdot L^{-1}$.	Simple for on-site use; retains micro- and macronutrients in fertilizer.	High energy demand for evaporation; significant ammonia loss without stabilization.
Membrane Distillation (MD)	Applies a temperature gradient across hydrophobic membranes for vapor transfer and nutrient concentration.	Water recovery up to 80%; ammonia rejection >95% under optimized conditions; energy demand of 180–240 $kWh \cdot m^{-3}$.	Low-grade heat usage; suitable for compact setups.	Fouling limits long-term usability; high ammonia volatility at high pH.
Electrodialysis (ED)	Uses electric fields and ion-exchange membranes to concentrate nutrients or remove specific ions like ammonium.	Energy demand as low as 1.3 $kWh \cdot kg\ N\text{-recovered}^{-1}$; nutrient concentration factors of ~6; nitrogen losses up to 50%.	Effective for nutrient recovery and micropollutant removal.	Fouling of membranes; nutrient losses to the diluate stream.
Air Stripping	Removes ammonia by increasing pH and temperature to facilitate volatilization.	Achieved >90% nitrogen recovery using pH > 10 and temperatures of 35–45°C; energy demand of 15–28 $kWh \cdot kg\ N\text{-recovered}^{-1}$.	Simple and efficient for large-scale applications.	Requires acid for ammonia recovery; large-scale infrastructure needed for optimal efficiency.

Ion-Exchange Adsorption	Uses materials like zeolites or biochar to adsorb ammonium ions for targeted nitrogen recovery.	Ammonium adsorption densities of 50–64 mg N·g^{-1} observed for zeolites and synthetic resins.	Compact setup; suitable for small-scale applications.	Requires regeneration; some materials have limited adsorption capacity for long-term use.
Precipitation Processes	Adds Mg^{2+} or Ca^{2+} to precipitate phosphorus as struvite or calcium phosphate.	Phosphorus recovery as struvite achieved >90% with Mg^{2+} addition; final product contained ~5% P (w/w).	Low-cost and straightforward; excellent for P-recovery.	Limited to P-recovery; may require additional nutrient recovery processes.
Nutrient Uptake by Algae	Cultivates algae in diluted urine for nutrient assimilation.	Maximum nitrogen uptake rate of 1300 g N·m^{-3}·d^{-1} and phosphorus uptake rate of 150 g P·m^{-3}·d^{-1} observed in optimized conditions.	Algae can be used as fertilizer or biomass; potential for CO$_2$ mitigation.	High space requirements; limited scalability due to dilution and post-processing challenges.

2.2. POLYMERS IN WASTEWATER TREATMENT

Bio-based polymeric materials have gained increasing recognition for their potential use in wastewater treatment. These materials offer advantages such as biodegradability, sustainability and safety. Research by Kolya and Kang (Kolya & Kang, 2023) highlighted the potential of polysaccharide-based polymers, particularly chitosan, in water treatment. However, challenges such as solubility issues and cost implications remain significant barriers. Stephen and Palanisamy (Stephen & Palanisamy, 2023) discussed the integration of biopolymers and biomaterials such as chitosan, activated carbon, carbon nanotubes and graphene oxide in wastewater treatment. These materials are noted for their unique attributes and effectiveness in the removal of pollutants. This study also highlights modifying biopolymers through grafting, functionalization and crosslinking to improve their performance. The author also highlighted the need for continued research to address practical application challenges and optimize the properties of these biopolymers for more efficient wastewater treatment.

Zubair and Ullah (Zubair & Ullah, 2021) reviewed the sustainability and efficacy of biopolymers such as cellulose, chitosan and keratin in removing contaminants from industrial wastewater. The review highlighted that these biopolymers are effective and

sustainable but scaling up their application for industrial use poses significant challenges. The author suggested that future research should focus on developing scalable and economically feasible methods to integrate these biopolymers into large-scale wastewater treatment processes.

Lee and Patel (Lee & Patel, 2022) reviewed the application of polymer microspheres as effective adsorbents for removing pollutants such as heavy metals and dyes from wastewater. The study emphasized the high adsorption capacities, environmental friendliness and stability of these microspheres. However, challenges remain, including high total dissolved solids (TDS) concentrations and the need for more effective toxicity reduction.

Table 2: *Summary of key points on application of Polymers in Wastewater Treatment.*

Polymer	Solubility	Cost	Performance	Reference
Chitosan	Water-soluble (depends on pH)	Moderate	Highly effective for removing heavy metals, dyes, and organic matter; biodegradable.	(Kolya & Kang, 2023; Zubair & Ullah, 2021)
Polyethylene oxide (PEO)	Water-soluble	Moderate to High	Useful in specific flocculation applications; limited by sensitivity to environmental factors.	(Kolya & Kang, 2023; Pramanik, 2000)
β-Cyclodextrin Polymer	Limited water solubility	High	Advanced adsorbent for micropollutants; outperforms activated carbon in adsorption rates and reusability.	(Alsbaiee et al., 2016; Yang et al., 2021)
Starch-based Polymers	Water-soluble	Low	Biodegradable and cost-effective; primarily used for low-to-moderate efficiency flocculation.	(Kolya & Kang, 2023; Zubair & Ullah, 2021)

| Superabsorbent Polymers (SAPs) | Water-absorptive (not soluble) | Moderate to High | Effective in dewatering and as moisture control agents; potential for passive chemical dosing systems in sanitation. | (Ignat et al., 2019; Mittal et al., 2022) |

2.3. DEGRADATION OF POLYMERS IN AQUATIC AND MARINE ENVIRONMENTS

The degradation of polymers in aquatic environments is a multifaceted process influenced by a range of physical, chemical, and biological factors. In their study published in 2002, Maria Rutkowska and her colleagues (Rutkowska et al., 2002) investigated the degradation of polyurethanes in seawater, paying particular attention to the role of crosslinking in the degradation process. The study revealed that the level of crosslinking significantly impacts the degradability of polyurethanes. It was found that higher crosslinking resulted in slower degradation. The research involved immersing polyurethane samples in seawater and a seawater-based liquid medium for up to 12 months and assessing changes in weight, tensile strength and morphology. The findings underscore that while polyurethanes can degrade in marine environments, the process is slow and influenced by the material's chemical structure. This research also highlighted the need for further studies to explore the degradation of polymers in a wider range of environments and over longer periods.

In a 2018 study, Da Costa and colleagues (Da Costa et al., 2018) investigated the degradation of polyethylene microplastics in artificial seawater. The researchers focused on the structural and morphological changes in polyethylene beads exposed to seawater, employing various analytical techniques, such as FT-IR and Raman spectroscopy. The results showed severe microcracking and the formation of oxidized groups on the surface of the polyethylene beads, indicating significant chemical and physical impacts due to accelerated exposure. However, the relatively short duration of the study (up to eight weeks) limits the understanding of long-term effects. The findings emphasize the importance of investigating the long-term degradation mechanisms of microplastics in marine environments to fully comprehend their environmental impact.

The abiotic degradation of polypropylene in the presence of excess water is influenced by various factors. Jakubowicz and colleagues (Jakubowicz et al., 2006) found that moisture can accelerate the degradation of polyethylene, but this process can be slowed down by ammonia and hydrogen peroxide. Kucharczyk and colleagues (Kucharczyk et al., 2016) observed that the degradation of polyurethanes based on Polylactic acid/Polyethylene glycol starts almost immediately in a water rich environment, with thermal decomposition occurring at temperatures above 230°C. Villamizar and Morillas (Arias-Villamizar & Vázquez-Morillas, 2018) noted that UV and temperature are significant promoters of degradation in high-density polyethylene, particularly in outdoor conditions. However, these plastics did not achieve complete disintegration or mineralization in aqueous environments.

Oxidation of Polypropylene:

-[CH$_2$CH(CH$_3$)]-$_n$ + O$_2$→Oxidized products (e.g., ketones, acids)

Where -[CH$_2$CH(CH$_3$)]-$_n$ is the repeating unit of PP.

Doi and colleagues (Doi et al., 1992) explored the biodegradation of microbial polyesters, particularly polyhydroxyalkanoates (PHAs), in seawater. The study found that these polyesters degrade through surface dissolution, with the rate of erosion being temperature-dependent. Furthermore, the researchers isolated actinomycetes strains from sea sediment capable of utilizing PHAs as a carbon source.

PLA degradation in water primarily involves hydrolysis, where water molecules cleave the ester bonds in the polymer chain, breaking it down into lactic acid. Kucharczyk and colleagues (Kucharczyk et al., 2016) studied the degradation behaviour of PLA-based polyester-urethanes, revealing that hydrolysis begins almost immediately upon exposure to water. They observed rapid degradation at 37°C and 55°C, indicating that higher temperatures accelerate the process, making PLA highly susceptible to water-induced degradation in warmer environments.
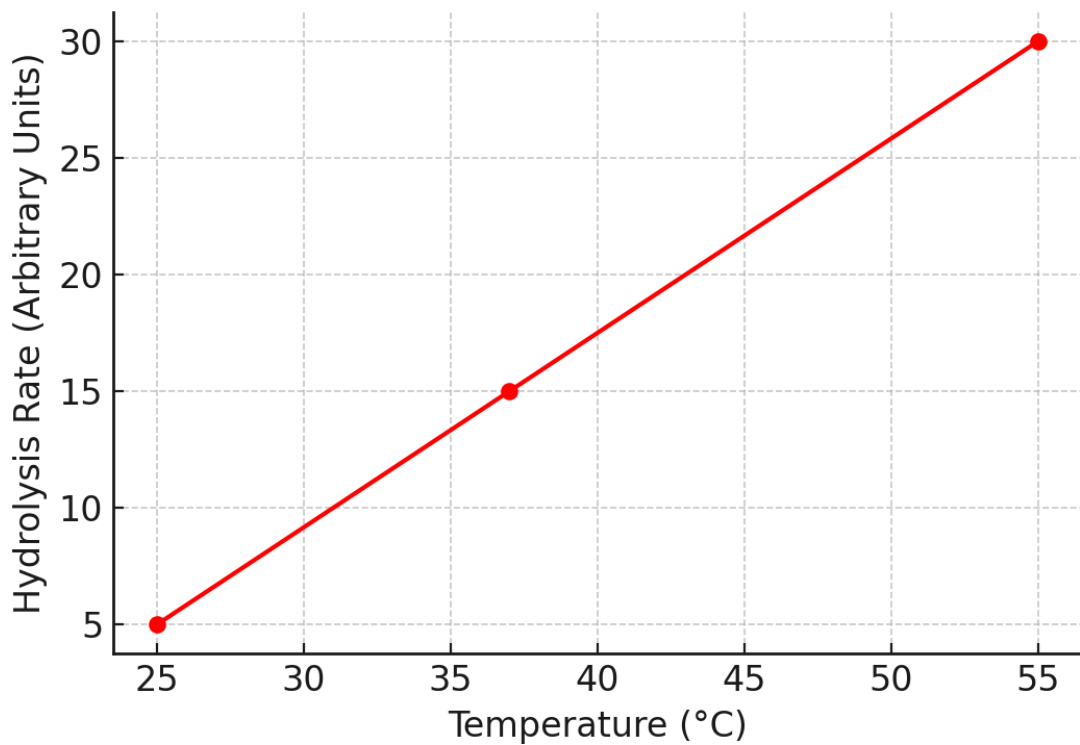
Figure 6: *Hydrolysis rates of polylactic acid (PLA) at various temperatures (25°C, 37°C, and 55°C). The rates increase with temperature, demonstrating the accelerated degradation of PLA at higher temperatures, which is crucial for waste management in varying environmental conditions.*

Similarly, Karjomaa and colleagues (Karjomaa et al., 1998) investigated the microbial degradation of PLLA oligomers and noted that abiotic hydrolysis to lactic acid is a crucial initial step. They emphasized that while biotic processes further break down the polymer, abiotic hydrolysis is essential for initiating degradation. This dual mechanism, involving both biotic and abiotic pathways, underscores the complexity of PLA degradation in aqueous environments.

Hydrolysis of Poly Lectic Acid:

-[OCH(CH₃)CO]-ₙ + nH₂O → nHOCH(CH₃)COOH
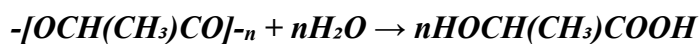
Where:

- -[OCH(CH₃)CO]-ₙ is the repeating unit of PLA.
- HOCH(CH₃)COOH is lactic acid.

The processes driving the degradation of PCL in the presence of excess water involve both abiotic and biotic mechanisms. The initial steps involve abiotic hydrolysis, which is facilitated by water molecules and leads to the breakdown of polymer chains into smaller

oligomers and monomers. This process renders the polymer more susceptible to enzymatic attack by microorganisms, which further degrade these fragments into carbon dioxide, water, and biomass. Haponiuk and Karlsson (Haponiuk & Karlsson, 2002) observed that PCL films were rapidly degraded in compost with activated sludge, highlighting the importance of microbial enzymes in the degradation process. They noted that microbial activity significantly accelerated the degradation compared to abiotic conditions, emphasizing that while water initiates the degradation process through hydrolysis, microbial activity is essential for complete assimilation of PCL in natural environments.

Hydrolysis of Polycaprolactone:

$$-[O(CH_2)_5CO]-_n + nH_2O \rightarrow nHO(CH_2)_5COOH$$
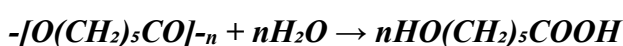
Where:

- $-[O(CH_2)_5CO]-_n$ is the repeating unit of PCL.
- $HO(CH_2)_5COOH$ is 6-hydroxyhexanoic acid.

Studies by Guzman-Sielicka et al. (Guzman-Sielicka et al., 2012) demonstrated that the presence of microorganisms significantly enhances PCL degradation in seawater. Their research showed that PCL degraded in all tested environments, but the process was more effective in biotic seawater than in abiotic conditions. They also found that modification of PCL with calcium carbonate (CaCO3) could inhibit its degradation, suggesting that specific additives can influence the degradation rate by either enhancing or inhibiting microbial activity.

Rutkowska and colleagues (Rutkowska et al., 1998) observed substantial biodegradation of PCL in natural seawater environments. Their study recorded changes in weight, tensile strength and morphology of PCL samples over several weeks, finding that these changes were more pronounced in seawater compared to buffered salt solutions. This suggests that natural seawater, with its diverse microbial community, provides a more conducive environment for PCL degradation than a controlled laboratory solution.

In subsequent studies, Heimowska and colleagues (Heimowska et al., 2017) reported complete assimilation of PCL in natural environments such as the Baltic Sea and compost with activated sludge. These findings highlight the high sensitivity of PCL to enzymatic attack by microorganisms in natural settings. The methodology involved incubating PCL

films in various environments and monitoring their degradation. They found that PCL was fully assimilated after seven weeks, indicating rapid biodegradation facilitated by microbial enzymes.

The environmental conditions under which PCL degradation occurs play a crucial role in determining the rate and extent of the process. Krasowska et al. (Krasowska et al., 2016) investigated the environmental degradability of PCL under various natural conditions and found that the degradation rate depended significantly on the specific environment and conditions. They observed that enzymatic hydrolysis of ester bonds in PCL was a key mechanism driving the degradation process. This study highlights the variability in degradation rates based on location and environmental factors such as temperature, pH, and microbial community composition.

Wu and colleagues (Wu et al., 2019) studied the anaerobic degradation of PVOH, describing it as a stepwise process that involves the breakdown of the polymer into smaller molecules such as ketones, fatty acids and alcohols. These intermediates are then further degraded into acetic acid, hydrogen and carbon dioxide leading to a comprehensive breakdown pathway. This underscores the potential for complete mineralization of PVOH in anaerobic conditions, making it a viable option for waste treatment in anaerobic environments.

Anaerobic Degradation of Polyvinyl Alcohol:

$-[CH_2CH(OH)]-_n \rightarrow$ *Ketones, fatty acids, alcohols* $\rightarrow$ *Acetic acid, H_2, CO_2*

Where $-[CH_2CH(OH)]-_n$ is the repeating unit of PVOH.

Chiellini et al. (Chiellini et al., 2006) investigated the impact of the degree of hydrolysis on PVOH's biodegradation behaviour. They synthesized various PVOH samples with controlled hydrolysis levels and tested their biodegradation in solid media. The results indicated that PVOH with lower hydrolysis degrees (25-75%) underwent more extensive mineralization compared to highly hydrolyzed variants. This suggests that the structural characteristics of PVOH significantly influence its degradation, with less crystalline and more amorphous structures being more susceptible to breakdown.

The presence of excess water, such as in textile wastewater, can enhance the biodegradation of PVOH. Chung et al. (Chung et al., 2016) investigated this by isolating two bacterial strains, *Microbacterium barkeri* KCCM 10507 and *Paenibacillus*

amylolyticus KCCM 10508, which were effective in degrading PVOH in textile wastewater. They found that a mixed culture of these strains was more efficient in removing PVOH and reducing chemical oxygen demand (COD) than single strains alone. This study highlighted the potential for bioremediation of PVOH-contaminated wastewater using specific microbial consortia.

In addition to biological degradation, PVOH can also undergo abiotic degradation through photochemical processes. According to Hamad et al. (Hamad et al., 2014), the degradation efficiency of PVOH in aqueous solutions can be significantly influenced by the feeding strategy of hydrogen peroxide. The study demonstrated that optimal feeding of H_2O_2 could enhance the breakdown of PVOH molecules, leading to effective degradation within a short time frame of 2 hours. This process primarily involves the generation of hydroxyl radicals that attack the polymer chains, leading to their fragmentation and eventual mineralization.

Photochemical Degradation of PVOH with H_2O_2:

-[CH$_2$CH(OH)]-$_n$+H_2O_2 → Oxidized fragments (via hydroxyl radicals)

Where -[CH$_2$CH(OH)]-$_n$ is the repeating unit of PVOH.

Table 3: Summary of key points on Degradation of Polymers in Marine Environments.

Polymer	Degradation Mechanism	Environmental Impact	Key Factors	Reference
Polyurethanes	Crosslinking reduces degradation rate	Persistent; slow degradation in marine environments	Crosslinking level, microbial activity	(Rutkowska et al., 2002)
Polyethylene (PE)	Microcracking, oxidation in seawater	Forms microplastics; environmental persistence	UV exposure, temperature	(Da Costa et al., 2018)
Polypropylene (PP)	Abiotic oxidation and hydrolysis	Partial degradation; forms microplastics	Moisture, temperature, UV exposure	(Jakubowicz et al., 2006)
Polylactic Acid (PLA)	Hydrolysis to lactic acid	Biodegrades under certain conditions	Temperature, pH, microbial enzymes	(Kucharczyk et al., 2016; Karjomaa et al., 1998)

| Polycaprolactone (PCL) | Hydrolysis and microbial enzymatic attack | Biodegradable in natural environments | Water presence, microbial diversity | (Haponiuk & Karlsson, 2002; Heimowska et al., 2017) |
| Polyvinyl Alcohol (PVOH) | Stepwise anaerobic degradation | Biodegradable under anaerobic conditions | Microbial consortia, water content | (Wu et al., 2019; Chiellini et al., 2006) |

2.4. PASSIVE TREATMENT OF WASTEWATER

The treatment of source-separated sanitation has garnered attention due to its potential for sustainable management of water, energy, and nutrient resources. Time-dependent passive chemical dosing systems have emerged as a promising solution for enhancing the efficiency of these systems. Kouzmanova and colleagues (Kouzmanova et al., 2002) explored the use of semi-permeable membranes for self-regulating chemical dosing in water and wastewater treatment plants. These membranes are particularly advantageous in situations with fluctuating water quantities or operational standstills as they can automatically adjust the dosing rate. The study highlighted the ease of installation and adaptability of these membrane dosing units to local conditions, making them practical for a variety of applications. This self-regulation capability addresses common issues associated with traditional dosing systems, such as high costs and maintenance challenges.

Sukhani and Chanakya (Sukhani & Chanakya, 2020) introduced a two-stage passive high-throughput sustainable sewage treatment process. This system combines primary anaerobic digestion with a secondary stage that removes protozoan and phytoflagellate bacteria along with residual organic material. The first stage emulates anaerobic purification through sludge upwelling, while the second stage employs a Euglena-driven process to achieve treated water quality. This approach is particularly useful in scenarios with space constraints and the need for low-maintenance, distributed treatment systems.

According to Etzel and colleagues's (Etzel et al., 1972) research, a system using synthetic fabric filters was developed to treat sanitary wastes at interstate highway rest areas, proving to be an effective and economical solution. This system produced high-quality effluent suitable for reuse in toilet flushing. However, the study also identified challenges such as the blinding phenomenon of the filter material and the impact of high

concentrations of detergents and waxes on filter performance. Despite these challenges, the system demonstrated significant potential for treating sanitary wastes efficiently.

2.5. MOISTURE ABSORPTION VIA SUPER-ABSORBENT POLYMERS

Super absorbent polymers (SAPs) have garnered considerable interest due to their remarkable water retention capacity, making them promising candidates for use as desiccants. One of the primary mechanisms through which SAPs function as desiccants is their ability to absorb and retain large quantities of water, making them highly effective in moisture control applications. Ignat et al. (Ignat et al., 2019) investigated the use of polymer-molecular sieve composites for air dehumidification and demonstrated high water adsorption capacity and independent humidity control. These composites are non-toxic and highly efficient, making them superior alternatives to traditional adsorbents. The composite matrices enhance water retention, offering a sustainable solution for humidity management in various environments.

Superporous gels (SPGs) represent another innovative application of SAPs. Mittal et al. (Mittal et al., 2022) introduced N-isopropylacrylamide (NIPAM) and acrylamide-based thermoresponsive SPGs, which exhibited interconnected capillary channels facilitating high water vapour transfer. With an adsorption capacity of 0.75 g/g at 25°C and 90% relative humidity, these SPGs showed excellent regeneration and reusability over ten continuous cycles, making them promising alternatives to conventional solid desiccants. The unique structure and high adsorption efficiency of SPGs position them as particularly effective in capturing water vapour from humid air.

The integration of SAPs into building materials represents a novel approach to passive humidity control. Fořt et al. (Fořt et al., 2020) examined the integration of SAPs into plasters to moderate indoor relative humidity levels. By adding up to 3 wt.% of SAPs, the water absorption coefficient of plasters was significantly increased, enhancing their ability to manage indoor moisture. This improvement in moisture buffering performance is crucial for maintaining healthy indoor air quality and mitigating the adverse effects of high humidity. These applications highlight the potential of SAPs in passive humidity control within building environments.

2.6. REMOVAL OF ORGANIC METABOLITES VIA POLYMERS

The removal of organic metabolites and micropollutants from water is a critical environmental challenge due to the persistence and potential toxicity of these substances. Superabsorbent polymers (SAPs) have emerged as promising materials for this purpose due to their high adsorption capacity and versatility. Sweetland (Sweetland, 1997) investigated the use of Hypersol-Macronet polymers, characterized by a bimodal pore size distribution and high oxygen-containing functional groups. These features enhance their effectiveness in adsorbing phenol and chlorophenols from water. The primary adsorption mechanism involves hydrophobic interactions and hydrogen bonding, resulting in strong interaction energies, particularly for chlorinated phenols. The study demonstrated high efficiency and potential for regeneration using organic solvents, suggesting commercial viability for water purification. However, there were practical limitations including the ineffective regeneration of certain polymer types, which could affect cost-effectiveness and broader application.

Alsbaiee and colleagues (Alsbaiee et al., 2016) developed a porous β-cyclodextrin polymer that showed rapid and effective removal of organic micropollutants, outperforming traditional activated carbon. The cross-linked β-cyclodextrin polymer exhibited adsorption rate constants 15 to 200 times greater than those of activated carbons and demonstrated excellent regeneration capabilities without performance loss. This polymer's structure allows for efficient sequestration of a variety of micropollutants, representing a significant advancement over conventional materials, particularly in terms of speed and reusability. The main challenges addressed by this study include the slow pollutant uptake and poor removal of hydrophilic micropollutants by activated carbons, as well as the energy-intensive regeneration process required for spent activated carbon.
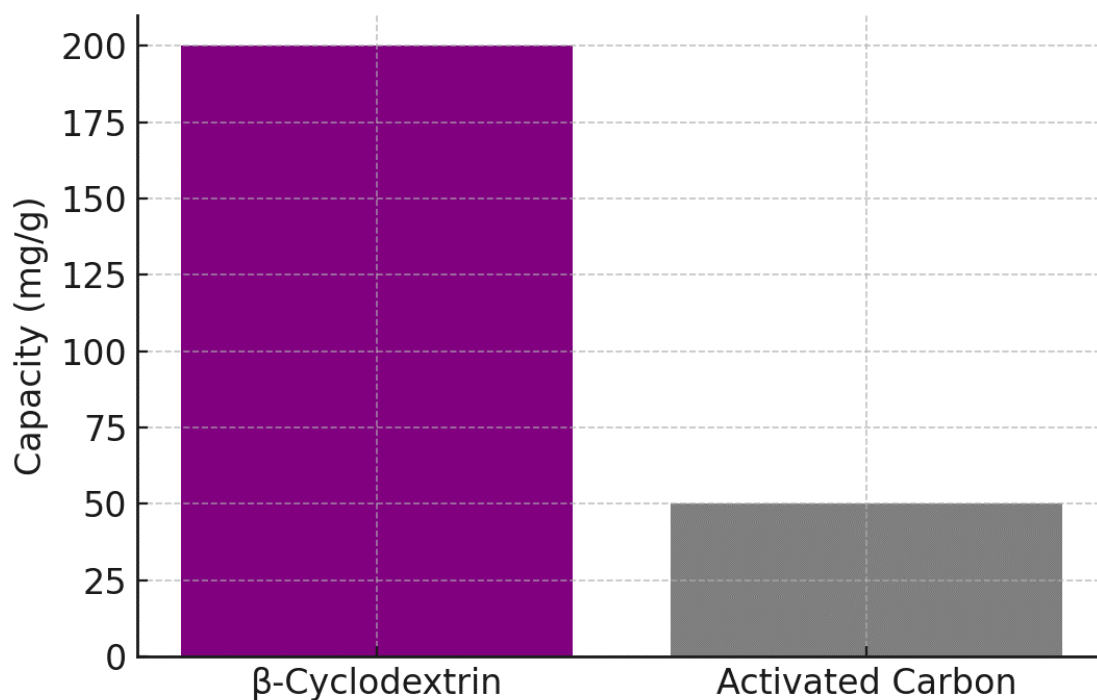
Figure 7: Adsorption Capacities of β-Cyclodextrin vs Activated Carbon. The bar chart compares the adsorption capacities of β-cyclodextrin polymers with traditional activated carbon. β-Cyclodextrin achieves 200 mg/g adsorption for various organic micropollutants, far surpassing the 50 mg/g of activated carbon. This showcases the enhanced speed and efficiency of β-cyclodextrin in water treatment.

Yang et al. (Yang et al., 2021) developed amide naphthotube-crosslinked polymers to remove polar organic micropollutants from water through biomimetic molecular recognition. These polymers demonstrated an efficient adsorption capacity for a wide range of micropollutants and could be easily regenerated with methanol or ethanol. The study emphasized the polymers' potential for water treatment applications but also highlighted the need for further research to explore variations in polymer design, scalability, and cost-effectiveness. Additionally, the study called for a deeper understanding of the regeneration process and its limitations.

Haddad et al. (Haddad et al., 2019) examined the potential of two hydrophobic polymeric resins for removing micropollutants in drinking water treatment. The resins demonstrated high efficiency, adsorbing over 80% of targeted micropollutants within 30 minutes. The study found that increasing the water temperature slightly improved micropollutant uptake and that the presence of natural organic matter did not affect the resins' efficiency.

However, the study did not directly compare with activated carbon or address long-term stability, regeneration or cost implications.

2.7. REMOVAL OF ORGANIC METABOLITES VIA ACTIVATED CARBON

Activated carbon has long been recognized as a highly effective material for the removal of organic micropollutants from water due to its high surface area and porous structure. Activated carbon adsorption plays a pivotal role in water treatment processes, particularly in the removal of micropollutants from both surface and groundwater sources. Haist-Gulde and colleagues (Haist-Gulde et al., 1995) emphasized the significance of optimizing operational conditions to enhance the efficiency of activated carbon. The study highlighted that the efficiency of micropollutant removal is significantly influenced by competitive adsorption between natural organic substances and trace organic compounds. Different trace organic compounds exhibit varying behaviours during the adsorption process, highlighting the necessity to understand the specific characteristics of the organic background and the pollutants for optimal performance.

Saha (Saha, 2005) explored the potential of modified activated carbons in improving the removal of heavy metals and organic compounds from aqueous solutions. The study demonstrated that oxidation of activated carbons significantly enhances their sorption capacity for heavy metals such as copper and organic pollutants such as herbicides. Modified activated carbons exhibit improved uptake of pollutants due to increased surface functionality and pore structure alterations. This research emphasizes the importance of surface modification in expanding the application of activated carbons for diverse water pollutants.

Djilani and colleagues (Djilani et al., 2016) examined the usage of activated carbon derived from animal bones for the removal of organic micro-pollutants. This type of activated carbon achieved a high removal rate, showcasing its potential as a cost-effective and sustainable alternative to conventional activated carbon. The high efficiency of bone-based activated carbon is attributed to its unique pore structure and high calcium content, which enhances the adsorption of certain organic compounds. This study opens avenues for the use of waste materials in producing effective adsorbents for water treatment.

2.8. FABRICATION OF BIOCHAR FROM HUMAN FECES AND REMOVAL OF MICROPOLLUTANTS USING BIOCHAR

The thermochemical conversion of human feces into biochar has emerged as an innovative approach to waste valorization and environmental management. Methods such as pyrolysis and hydrothermal carbonization (HTC) are widely employed, with each technique offering distinct advantages. Pyrolysis involves heating fecal matter under oxygen-limited conditions, typically between 300°C and 700°C, resulting in carbon-rich biochar with enhanced surface area and adsorption capacity (Dominguez et al., 2020). Funke and Ziegler conducted HTC at moderate temperatures (180–250°C) under high pressure, producing biochar directly from wet waste, and retaining essential nutrients such as nitrogen and phosphorus (Funke & Ziegler, 2010). Mumme and colleagues found that pre-treatments, including the addition of alkalis or acids, can further enhance the functional properties of the biochar, augmenting its potential for applications such as pollutant removal and soil amendment (Mumme et al., 2015). Biochar's utility extends to the adsorption of micropollutants from water, attributed to its high surface area, porosity, and functional group diversity. Removal mechanisms include hydrophobic interactions, π-π stacking, and electrostatic attraction, effectively targeting pharmaceuticals, heavy metals, and endocrine-disrupting compounds (Ahmad et al., 2020; Lee et al., 2018). Lee and colleagues found that chemical activation utilizing acids or bases, surface functionalization with amino or thiol groups, and integration into composites with graphene or metal oxides demonstrated improvements in biochar's adsorption capacity and specificity (Lee et al., 2018). Despite these advancements, challenges such as competition from natural organic matter and limited reusability impede large-scale implementation. Research into scalable production and efficient regeneration techniques remains crucial for integrating biochar into sustainable wastewater treatment systems.

2.9. HUMAN URINE AS A CHEMICAL RESOURCE

Randall and team developed a method to produce bio-bricks using microbial induced calcium carbonate precipitation, utilizing urea from stabilized human urine (Lambert & Randall, 2019). This process achieved a maximum compressive strength of 2.7 MPa, comparable to conventional bricks. Urine has also been successfully used in bioelectrochemical systems as an electrolyte and organic substrate, offering potential for

energy recovery and nutrient concentration by Santoro and colleagues (Santoro et al., 2020). Additionally, researchers have demonstrated that human urine can be transformed into highly porous carbon containing heteroatoms, which exhibits superior electrocatalytic activity for oxygen reduction reactions compared to platinum-based catalysts (Chaudhari et al., 2014). Traditionally, human urine played a crucial role in traditional leather tanning processes. The ammonia in urine acted as a natural alkaline agent, essential for softening animal hides and removing hair during the initial stages of tanning. This process was called bating and helped prepare the hides for further chemical treatments to create durable leather. In Europe and parts of Asia, urine was a readily available and cost-effective resource for small-scale tanneries before the advent of synthetic chemicals (Smithsonian, n.d.; urotherapyresearch.com, n.d.). Urine was also extensively used as a mordant in the dyeing industry. The ammonia content stabilized dyes on fabrics, enhancing their colour fastness and vibrancy. This application was particularly common in regions where natural dyes derived from plants and insects were utilized, such as indigo or cochineal (Smithsonian, n.d.).

Table 4: *Summary of key points of the Review of Literature.*

Topic	Techniques/Materials	Key Findings	Challenges	Reference
Nutrient Recycling from Urine	Nitrification-distillation, forward osmosis, microbial electrochemical processes, alkaline dehydration	High recovery of nitrogen, phosphorus, potassium; energy-efficient fertilizer production; scalable potential	Membrane fouling, energy optimization, ammonia volatilization, pre-treatment requirements	Udert & Wächter (2012), Zhang et al. (2014), Simha et al. (2020), Tao et al. (2019), Viskari et al. (2018)
Polymers in Wastewater Treatment	Bio-based polymers (chitosan, cellulose, keratin), polymer microspheres	Effective pollutant removal (e.g., heavy metals, dyes); biodegradable, sustainable materials	Scaling up for industrial use, solubility issues, cost implications	Kolya & Kang (2023), Stephen & Palanisamy (2023), Zubair & Ullah (2021)
Degradation of Polymers in Aquatic Environments	Hydrolysis, microbial enzymatic activity, abiotic factors (UV, temperature, oxygen)	Degradation depends on polymer type, crosslinking, and	Slow degradation in abiotic conditions, incomplete	Rutkowska et al. (2002), Kucharczyk et al. (2016), Heimowska

		environmental factors; some achieve rapid biodegradation	mineralization in some plastics	et al. (2017), Chung et al. (2016)
Passive Wastewater Treatment	Time-dependent chemical dosing systems, Euglena-driven processes, synthetic fabric filters	Low-maintenance systems suitable for distributed wastewater management; adaptable to local conditions	Filter fouling (blinding), detergent interference, limited scalability	Kouzmanova et al. (2002), Sukhani & Chanakya (2020), Etzel et al. (1972)
Superabsorbent Polymers for Moisture Control	Polymer-molecular sieve composites, superporous gels (SPGs), SAP-enhanced plasters	High moisture absorption and retention; regeneration over multiple cycles; improved indoor humidity control	Performance under varying environmental conditions, integration into construction materials	Ignat et al. (2019), Mittal et al. (2022), Fořt et al. (2020)
Removal of Organic Metabolites	β-cyclodextrin polymers, amide naphthotube-crosslinked polymers, hydrophobic resins	High adsorption efficiency; rapid uptake; effective regeneration capabilities	Long-term stability, comparative cost-effectiveness with activated carbon	Alsbaiee et al. (2016), Yang et al. (2021), Haddad et al. (2019)
Human Urine as a Resource	Microbial-induced calcium carbonate precipitation (MICP) and stabilized urine; Urine as an electrolyte and organic substrate in bioelectrochemical systems; Conversion of urine into porous carbon materials with heteroatoms	Bio-bricks with compressive strength comparable to conventional materials; Nutrient concentration and energy recovery; Superior electrocatalytic activity for oxygen reduction reactions compared to platinum-based catalysts	Scalability and optimization for commercial applications, Long-term stability and energy efficiency optimization, Cost-effectiveness and scaling for industrial applications	Lambert & Randall (2019), Santoro et al. (2020), Chaudhari et al. (2014).

2.10.   RESEARCH GAP

The extent of research on sustainable sanitation and water management has made substantial progress in encompassing the application of polymers in diverse environmental contexts, including water recycling and material degradation. However, a significant void persists in the precise application of polymer-based systems for alkaline urine dehydration. The challenges associated with pH buffering of dehydrating alkaline urine and water recycling in circular urine dehydrating systems have not been thoroughly examined. The current literature lacks comprehensive investigations on the long-term stability, degradation mechanisms, and performance of various polymers—especially in environments characterized by high alkalinity and fluctuating temperatures—typical of urine dehydration processes.

Furthermore, the integration of superabsorbent polymers (SAPs) for water recycling from urine source-separating systems has been minimally addressed, especially concerning their capacity to maintain pH stability and remove organic metabolites from reclaimed water. This thesis aims to bridge these gaps by exploring the application of polymer pouches for the controlled addition of pH-buffering chemicals during the alkaline dehydration of urine. By evaluating the degradation behaviour of diverse polymers in both concentrated and unconcentrated urine, the research aims to identify the most appropriate materials for constructing passive chemical dosing systems.

The current research aims to investigate the degradation of Poly-L-lactic acid (PLLA) in the context of various factors such as polymer film thickness, crystallinity, urine pH, and temperature, to optimize the polymer's performance in urine dehydrating conditions. Furthermore, the study assesses the efficacy of polymer pouches in regulating urine pH over an extended period, taking into account variables like the number of pouch layers and urine concentration. Additionally, the research evaluates a circular urine dehydrating setup that is novel, focusing on its ability to buffer pH and remove organic metabolites while recycling water. The study also examines the system's overall energy efficiency, addressing a significant gap in the current literature where the majority of energy loss in similar systems is often overlooked.

By exploring these understudied areas, this thesis not only contributes to the advancement of polymer-based technologies in sanitation but also proposes innovative solutions to enhance the sustainability and efficiency of urine dehydration processes, particularly in

resource-constrained environments. The findings of this study will provide valuable insights for the development of more resilient, scalable, and energy-efficient systems, addressing the urgent need for sustainable water management solutions in the face of global environmental challenges.