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Characterization and treatment of industrial laundry wastewaters: a review

Grégorio Crini¹  · Dario Lacalamita^{1,2}  · Eric Lichtfouse³  · Nadia Morin-Crini¹  · Chong Liu⁴ · Lee D. Wilson⁵ · Lorenzo A. Picos-Corrales⁶  · Mabel Amen Akhere⁷ · Maria Sotiropoulou⁸ · Corina Bradu⁹ · Chiara Mongiovi¹⁰ 

Abstract

The industrial laundry sector is a major user of water and chemicals such as surfactants, and one of the largest producers of wastewater. Although treated wastewaters comply with regulations, they still contain contaminants. Here we review laundry wastewater with focus on industrial laundry activities and their challenges, chemical composition of wastewater, and treatment techniques. We discuss advantages and drawbacks of treatment techniques that can be used as secondary treatment in already existing plants, or as tertiary treatment, i.e., complementary to an existing treatment. We observe that laundry is an expanding industrial sector with increasing water requirements, an abundant use of chemical substances, and increasingly stringent discharge regulations. There is a lack of chemical and biological knowledge on aqueous discharges. Moreover, the chemical composition, temporal variability, treatment information, and environmental and ecotoxicological data are poorly reported. The composition of wastewaters and additives, and their temporal variability are also poorly known. Similarly, detailed information on treatments is rare, and environmental and ecotoxicological data are poorly reported. Finding a tertiary water treatment process that is efficient, viable, and environmentally friendly is challenging since wastewater volumes are very high and contaminants are present at trace level in complex organo-mineral mixtures.

Keywords Greywater · Complex contamination · Water quality assessment · Wastewater treatment plant · Discharge water · Integrated treatment · Laundry wastewater · Organo-mineral · Pollutant · Surfactant

Introduction

Water is under increasing threat from various anthropogenic activities. Among these, the industrial laundry sector is considered one of the largest users of water and chemicals, and therefore one of the largest producers of wastewaters (Braga and Varesche 2014; Bering et al. 2017; Peña-Guzmán et al. 2019; Patel et al. 2020; Jayanto et al. 2021; Santiago et al. 2021; Luo et al. 2022; Procházková and Máša 2022; Kumar et al. 2022; Melián et al. 2023; Vishali et al. 2023). In Europe, industrial laundry sector washes 2.7 billion kg of textiles per year and uses 42 million m³ of water (Melián et al. 2023). In China, the amount of laundry wastewater discharged annually is estimated to 11 billion tons (Luo et al. 2022). Due to the use of many commercial formulations containing chemicals of varying nature, wastewater from this industrial sector is known for its polycontamination both qualitatively and quantitatively with both particulate

and dissolved forms. Among these substances, the family of surfactants, generally of anionic type, are often cited in the literature, with concentrations in wastewater ranging from a few mg to several g per L of water (Janpoor et al. 2011; Abd El-Gawad 2014; Delforno et al. 2014; Babajanzadeh et al. 2019; Kaya and Dayanir 2020; Pandey et al. 2020; Akarsu and Deniz 2021; Khan 2022; Lacalamita et al. 2023).

Despite these varying concentrations, in all cases, the laundry sector, like any other industrial sector, must treat its wastewater, heavily contaminated by chemical and biological substances, before being released into the environment. The discharge of wastewater is indeed governed by specific regulations for this industrial sector. Most laundry effluents are first treated internally at the industrial treatment plant and then released to municipal sewer systems, where they are further treated at local wastewater treatment facilities that often use activated sludge as secondary treatment, the water treatment system conventionally used in the urban wastewater treatment plants. Even if their treated wastewaters comply with current regulations, they

still contain measurable quantities of heterogeneous contaminants such as surfactants, which can impact the performance of activated sludge. Because of their many physical and chemical properties which are highly useful in washing processes (Abd El-Gawad 2014), surfactants are widely used worldwide. These active agents are classified in the family of emerging contaminants.

Urban treatment plants have not been designed to remove these emerging substances (Khan 2022; Morin-Crini and Crini 2017; Gogoi et al. 2018) and release much of them into the environment. Thus, these molecules and their metabolites are found in the aqueous compartments, and are the subject of debate, particularly as regards their degradation and accumulation. However, for the moment, there are no specific regulations for manufacturers in terms of analytical monitoring of these molecules. Nevertheless, several target substances present in complex commercial formulations are regulated and can be monitored, such as alkylphenols and their polyethoxylated derivatives, organic fluorinated substances (PFAS), polybromodiphenylethers (PBDE), and formaldehyde. Some of which are little or no biodegradable, may induce ecotoxic effects and are known as endocrine disruptors since they mimic natural hormones by interacting with estrogen receptors. The European Union has included these substances in the list of priority hazardous substances for surface waters in the Water Framework Directive (Directive 2000/60/EC). Currently, Europe is asking manufacturers to innovate to reduce and/or eliminate chemicals, in particular emerging contaminants, in their discharge waters (Morin-Crini and Crini 2017). Before implementing actions to eliminate these substances, laundries must have knowledge of the chemical composition of their wastewater and discharge water. On this point, however, bibliographic data on the detailed composition of the waters of this industrial sector and their temporal variability are scarce (Abney et al. 2021; Sheth et al. 2021; Lacalamita et al. 2023).

Today, industrial laundries are also more aware of their water consumption and the need to prevent pollution of this resource, and are looking for alternative or complementary solutions to reduce their environmental impact. However, finding a tertiary water treatment process that is efficient, viable, and environmentally friendly is a real challenge for this sector, since wastewater volumes are very high and contaminants are present in trace form in complex organo-mineral mixtures. Moreover, water contamination is both chemical and biological, and contaminants can be found in dissolved or particulate form (microfibers, colloids) in wastewaters of varying pH, viscosity and temperature. Over the last decade, many works have been published on the treatment of raw wastewater and discharge from the laundry sector, with notable contributions (Table 1). However, detailed information on the type of water treatment is rare, as each laundry has its own treatment method and know-how

for decontaminating its wastewater (Ho et al. 2021). Regulatory, environmental and ecotoxicological data are also poorly reported in the literature. As far as we know, no effort has been made to collect these results to make them easier to understand. That is the purpose of this article, which attempts to answer the questions raised.

The review comprises three main sections. After a brief presentation of the context, the first part provides a summary of industrial laundry operations and the issues surrounding its aqueous discharges. This part also describes the regulations and the environmental challenges. The second section lists chemicals that are likely to be found in the water and summarizes the environmental issues facing this industry. It also describes data on the chemical composition of the water. Finally, the last part focuses on the technologies used for wastewater treatment, illustrated by an example of a general wastewater treatment scheme. Then, we discuss the benefits and drawbacks of water treatment, which can be used as tertiary treatment that is, in addition to existing treatment or secondary treatment in plants that already exist. The review will serve as a guide for future researchers working on industrial laundry water. Nevertheless, the subject of microfibers in water is not covered in this review, as it has been the subject of numerous publications over the last decade (e.g., Prata 2018; Gatidou et al. 2019; Liu et al. 2019; Vassilenko et al. 2019; Sun et al. 2019; Bretas Alvim et al. 2020; Gavigan et al. 2020; Ramasamy and Subramanian 2021; Turan et al. 2021; Kwak et al. 2022; Le et al. 2022; Belzagui and Gutiérrez-Bouzán 2022; Allen et al. 2024; Arif et al. 2024). Furthermore, there are currently no regulations governing this type of pollution in the industrial laundry sector.

Industrial laundries

Context

Industrial laundries are establishments that treat linen in an industrial way by cleaning it with large quantities of water and cleaning products containing different chemicals, which are used not only to improve the efficiency of the cleaning cycle, but also to reduce water and energy costs and improve the service life of the machines used. Their clientele is mainly established by professional companies, and the dirty linen comes from various sources such as hospital sheets, hotel linen, restaurant towels and tablecloths, work clothes and working uniforms, shop towels, and textiles from beauty salons. In general, the principle of linen treatment is the same, but it can be modulated according to the type of the treated linen, the degree of soiling, the used products, e.g., detergents, softeners and bactericides, and the know-how and experience of each laundry (Bering et al. 2011; Braga and Varesche 2014; Dąbkowska 2017; Sheth et al.

Table 1 Recent literature reviews on laundry wastewater and topics covered

Review title	Topics and keywords	Comment	References
Greywater characteristics, treatment systems, reuse strategies and user perception	Greywater composition, user perception, treatment methods, reuse	The authors reviewed innovative treatment technologies, reuses strategies and perception of greywater reuse among users	Oteng-Peprah et al. (2018)
Ozonation treatment processes for the remediation of detergent wastewater	Advanced treatment, oxidation, catalytic ozonation, detergent	This review summarizes studies on ozonation treatment of surfactants and their translation laboratory-scale to real-scale operation processes	Joseph et al. (2021)
Water pathways through the ages: Integrated laundry wastewater treatment for pollution prevention	Integrated-treatment process, water reclamation, sustainable process development	This study describes the feasibility of current laundry wastewater treatment technologies and the experience of various countries in adopting different approaches	Ho et al. (2021)
Laundry wastewater treatment: Review and life cycle assessment	Conventional and advanced treatment methods, life cycle assessment, water reclamation	The review discusses and assesses the life cycle of various laundry wastewater treatment methods, focusing on their environmental impacts, effectiveness, and economic viability	Santiago et al. (2021)
Advancements in laundry wastewater treatment for reuse	Treatment technologies, advanced oxidation, ultrafiltration, reclamation, reuse	The authors discuss the role of several treatment methods to treat laundry wastewater and solutions for reclamation	Kumar et al. (2022)
Management of greywater: Environmental impact, treatment, resource recovery, water recycling, and decentralization	Decentralized treatment system, environmental impacts, grey wastewater management, resource recovery	The review focuses on the management, treatment, and resource recovery for recovery of grey wastewater, highlighting its potential for recycling and the environmental benefits of decentralized treatment systems, particularly in water-scarce areas	Khajvand et al. (2022)

2017; Babajanzadeh et al. 2019; Furtado et al. 2020; Lutterbeck et al. 2020; Abney et al. 2021; Jayanto et al. 2021; Khajvand et al. 2022; Khan 2022; Khery et al. 2022; Kumar et al. 2022; Lacalamita et al. 2023).

In Europe, there are about 11,000 industrial laundries, with more than 90% small and medium-sized enterprises employing 170,000 workers (source: European Commission- <https://ec.europa.eu/eurostat/web/products-eurostat-news/-/edn-20220627-1>). They are a particular, confidential, competitive, and booming industrial sector with significant human resources, energy, chemicals, and water needs. The water consumption is estimated at more than 40 million m³ per year, and therefore, the industrial laundry sector is considered one of the largest producers of wastewater, which is considered a primary pollution source (Oteng-Peprah 2018; Barumbu et al. 2020; Santiago et al. 2021; Kumar et al. 2022; Procházková and Máša 2022; Melián et al. 2023; Pang et al. 2023; Vishali et al. 2023). All the generated wastewater is decontaminated in industrial wastewater treatment plants before being released into the environment.

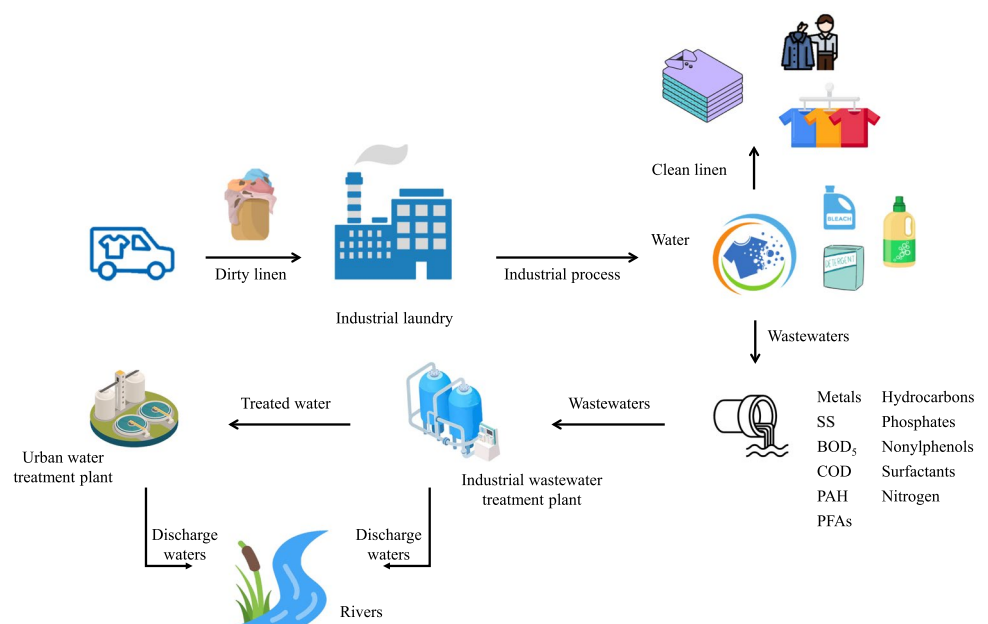
Figure 1 illustrates the water circuit in an industrial laundry, from collection to treatment in a wastewater treatment plant and discharge. Industrial laundries are often located on the periphery of cities, which is why the treated water is often sent to the urban water treatment plant of a city. In Europe, wastewater from laundries is considered to be of similar quality as urban wastewater. Therefore, it can be discharged into municipal wastewater treatment plants via a discharge agreement (Lacalamita et al. 2023).

To treat wastewater from the industrial laundry sector, the two decontamination processes often encountered are physicochemical and biological treatments or a combination

of both. For confidentiality reasons, these techniques are rarely detailed in the literature (Ho et al. 2021; Lacalamita et al. 2023). Even if the treated wastewater complies with the regulations in force, it still contains a significant amount of chemicals, which is why this industrial sector is responsible for discharging potential toxic organic and inorganic substances, oxidizable materials, and nutrients into the environment. This cocktail of chemicals may raise concerns about possible environmental risks when the treated water is discharged (Ivanković and Hrenović 2010; Abd El-Gawad 2014; Rebello et al. 2014; Verlicchi et al. 2015; Swartz et al. 2017; Furtado et al. 2020; Tomšič et al. 2023). A review of the bibliographic data shows that precise data concerning the pollution in terms of qualitative and quantitative fluctuations in discharge water from the laundry sector have seldom been reported (Abney et al. 2021; Sheth et al. 2021; Lacalamita et al. 2023).

Treated waters sent to urban treatment plants can also cause problems because the presence of certain potentially hazardous components can inhibit the behavior of bacteria, for example, disturbing nitrification processes. Indeed, certain bacteria are highly sensitive to recalcitrant organic substances and metals such as copper, nickel, chromium, and iron (Malik 2004; Morin-Crini and Crini 2017; Bala et al. 2022; Khan 2022). In France for example, in the discharge agreement, it is stipulated that the ratio of COD and BOD, i.e., a biodegradability index used as an indicator of water toxicity, must be less than 2.5, a reference value indicating the biodegradability of water and the presence of target metals such as copper, zinc and nickel and the amount of suspended solids is strongly controlled, in order to avoid problems in filtration processes and biological tanks of urban wastewater

Fig. 1 The water circuit in an industrial laundry, from its use to its treatment and discharge. The water treated in the industrial treatment plant is either discharged into the river or sent to the urban water treatment plant of the city via a discharge agreement. SS: suspended solids; BOD₅: biochemical oxygen demand, 5-day test; COD: chemical oxygen demand; PAH: polycyclic aromatic hydrocarbons; PFAs: perfluoroalkyl and polyfluoroalkyl substances



treatment plants (Morin-Crini and Crini 2017; Lacalamita et al. 2023). Other components present in wastewater such as microplastics and microfibers can affect the treatment process, as because wastewater treatment techniques can break these particles into nanoparticles (Enfrin et al. 2019). Particles moving through wastewater treatment plants experience variable shear forces induced by mixing or pumping, which can break them into other smaller particles, then increasing the number of nanoparticles in the rejections. In addition, in the early stages of treatment processes, high concentrations of particles in water can impact the performance for water treatment processes such as filtration units that may be clogged or damaged due to clumping or wear of the particles (Morin-Crini and Crini 2017). However, flocculation is a standard low-cost stage appropriate for reducing the impact of microplastic on the rest of the water treatment process (Huang et al. 2023a). On the other hand, an excessive presence of ionic surfactants can also reduce treatment performance, for example by altering particle sedimentation through changes in their surface characteristics (Huang et al. 2023b). Surfactants can also disrupt the primary sedimentation process and reduce oxygen transfer capacity in biological treatment tanks. Surfactants present a complex challenge for removal and can be removed by degradation or adsorption processes (Jardak et al. 2016) although their removal is more difficult than that of microplastics and microfibers. Finally, regulatory, environmental and ecotoxicological data are also poorly reported in literature.

Faced with increasingly stringent regulations and challenges related to the economy, energy, and society, industrial laundries must adapt and evolve through technological advancements and operational changes (Ho et al. 2021; Kumar et al. 2022; Procházková and Máša 2022; Atesci and Inan 2023; Chen et al. 2023; Konečná et al. 2023; Lacalamita et al. 2024). The challenges facing the sector include the following: using more environmentally-friendly cleaning processes and eco-friendly products while maintaining linen quality; using less water in the washing process and recycling more treated wastewater; using more energy-efficient machines; comply with increasingly stringent health and safety standards requiring specific disinfection or sterilization treatments (as in the case of hospital, retirement home or hotel linen); improve the operation of their wastewater treatment plants; reduce the flow of pollutants discharged (including CO₂ emissions) and minimize their impact on the environment.

All these challenges and problems affect the operational practices of industrial laundries, which depend mainly on the type of laundry to be cleaned and the level of dirt. Each laundry must adapt its way of working according to the trend and its objectives mentioned above by offering more sustainable and responsible solutions to meet the growing demands of its customers (Furtado et al. 2020; Lutterbeck et al. 2020;

Abney et al. 2021; Jayanto et al. 2021; Khajvand et al. 2022; Khery et al. 2022; Kumar et al. 2022). But this adaptation must also be part of a more general framework because it is necessary to take into account all the professional risks of the trade. Industrial laundries collect and process dirty laundry (washing, drying, ironing, folding) and ship it back to their customers. The processes use machines (washers, dryers) emitting heat and moisture and chemicals (detergents, stain removers and disinfectants) whose characteristics (volatility, acidity, alkalinity, corrosive, irritating or allergenic characters) are highly variable from one product to another. Staff work in a prolonged standing position and require many manual handling, postural constraints and repetitive gestures. Staff involved in sorting dirty laundry (which has the ability to fix microorganisms) are also in contact with microbiological agents that are sources of infection and disease. These agents come from laundry soiled or contaminated with biological fluids (blood, urine) or unwanted objects (needles). Staff are thus exposed to various occupational risks: thermal (exposure to high heat released by equipment), chemical (allergies and skin and respiratory irritations), biological (infectious, viral or parasitic diseases) and physical (osteoarticular damage, trauma caused by falls on wet ground, burns) which are very common. Industrial laundries are also technical rooms with a high risk of fire (risk of self-ignition of linen by fermentation, ignition of textile dust in dryers, stocks of chemicals or oxidizing detergents) and electrical malfunctions. Industrial laundries must therefore constantly develop appropriate collective and individual training, good practice and prevention policies. Examples of actions that are implemented are the compliance of machines that must be properly used, well maintained and regularly monitored, the choice of technologies favoring eco-responsible practices (limit water consumption, reduce energy consumption, use products and processes with a lower potential impact on humans, limit gas emissions), respect for hygiene rules, wearing protective clothing and accessories (gloves, gowns, shoes) adapted to each position as well as ergonomic equipment, continuous training of staff, regular control of the risks of biological contamination, and the presence of adequate air extractions and fire protection systems in the premises (McIlwraith et al. 2019; Belzagui and Gutiérrez-Bouzán 2022; Le et al. 2022; Konečná et al. 2023).

Initiatives have already been implemented in Europe, such as eco-detergent certification (EU Ecolabel) or the use of solar energy and cogeneration sources for laundry operations (Buehler et al. 2021; Belzagui and Gutiérrez-Bouzán 2022; Procházková and Máša 2022; Konečná et al. 2023; Melián et al. 2023). In Europe, a thousand detergents have an eco-certification, attesting to their biodegradability (Melián et al. 2023). A recent French law called anti-waste for a circular economy (AGEC Law—*loi anti-gaspillage pour*

une économie circulaire; decree no. 2022–336 of 10 March 2022) aims to change the production and consumption model in order to preserve natural resources and biodiversity (Lacalamita et al. 2024). This law encourages manufacturers to continue their efforts to reduce their environmental impact. However, initiatives concerning water engineering and treatment in an integrated approach to pollution prevention are rare due to the complex and heterogeneous nature of water, the large volumes of water to be treated daily, as well as technological and economic constraints (Kim et al. 2022; Khapra et al. 2023). While there are many well-known tertiary treatment methods, including membrane filtration, advanced oxidation and evaporation, very few are actually employed because the costs associated with maintenance and operation are just as significant as the initial expenditure (Morin-Crini et al. 2022; Melián et al. 2023). Qualified personnel is also required. Furthermore, skilled workers are needed.

Over the last decade, many works have been published on the treatment of raw wastewater and discharge from the laundry sector (e.g., Oteng-Peprah et al. 2018; Ho et al. 2021; Santiago et al. 2021; Khajvand et al. 2022; Violenta et al. 2022; Akhere and Chukwuka 2023; Atesci and Inan 2023; Kumar et al. 2022, 2023; Melián et al. 2023; Cahayani et al. 2024), but few articles have been devoted to their chemical composition and fluctuations (Sheth et al. 2017; Jayanto et al. 2021; Alhinaï 2022). Increasing awareness of water pollution and resource scarcity has stimulated research into conventional and non-conventional treatment methods not yet in use in the laundry sector, such as adsorption onto innovative adsorbents, advanced oxidation, and membrane filtration or a combination of methods to enable greater efficiency (Morin-Crini et al. 2022). The combination of established treatment methods is indeed proving increasingly and necessary. Several studies have been published on the value of combining complementary physical and chemical methods. Janpoor et al. (2011) described the potential of combining electrocoagulation with adsorption for enhanced removal of both organic pollutants and metals.

Similarly, a study by Nascimento et al. (2019) demonstrated the effectiveness of coupling membrane filtration with coagulation. This synergistic approach allowed to obtain higher elimination rate for surfactants and microplastics compared to individual methods. Innovative techniques such as advanced oxidation (ozonation) and photocatalysis are gaining ground because of their ability to completely degrade pollutants to mineralization if this is the desired objective (Oliveira Schwaickhardt et al. 2017). Electrocoagulation and electrooxidation are also promising options (Dimoglo et al. 2019; Ho et al. 2021). A study by Dimoglo et al. (2019) demonstrated the effectiveness of electrocoagulation in removing surfactants and achieving color reduction in laundry wastewater. These electrochemical and advanced

oxidation methods are promising, but the initial investment and high operational costs still limit their feasibility on an industrial scale, unlike membrane filtration methods that are beginning to take root (for example, in some French laundries) despite the fact that they also consume energy. Indeed, the progress of ultrafiltration and nanofiltration with compact and easy-to-use equipment for small industrial structures make it possible to consider these techniques to more effectively eliminate trace of contaminants while being economically viable and through a water recycling route. Nanofiltration, studied by Kaya et al. (2020), has also shown promising results in the removal of emerging contaminants from laundry effluent. Whatever the method, a complete understanding of the environmental footprint is necessary. Further research is also needed to conduct in-depth life cycle assessments that assess factors such as energy consumption, resource use and waste generation throughout the life cycle of each method (Ho et al. 2021).

To the best of our knowledge, there is no comprehensive review that summarizes and discusses the published results. Out of 204,342 documents published on wastewater characterization and treatment from January 2000 to December 2023, only 309 focus on the study of laundry wastewater, representing less than 0.2% of the total corpus. In particular, specifics, as showed in Fig. 2, based on a comparison of grey water and industrial wastewater from 2000, it is becoming apparent that efforts to explore chemical composition and potential treatment methods for treating laundry effluents are minimal compared to their counterparts. Our objective in this review is to provide a brief summary of industrial laundry operations, listing general considerations and environmental challenges posed by their aqueous discharges. Moreover, it identifies chemicals that are likely to be found in water and discusses the broader environmental impacts of the laundry industry. Additionally, this study describes the discharge water quality of the laundry industry and the corresponding regulations from different countries. It also outlines typical wastewater treatment schemes and evaluates both the advantages and limitations of tertiary treatment methods, which can complement existing primary and secondary treatments in established facilities.

Definition and classifications

Industrial laundry is a service industry, strongly established in Europe, that treats dirty linen in an industrial way (Dąbkowska 2017; Bering et al. 2017; Procházková and Máša 2022). This term refers to laundering activities on a large scale for large institutions that require a constant flow of clean linen, work wear, or uniforms. So industrial laundries play an essential role in various businesses such as hospitals, nursing homes, hotels, restaurants, and factories (Kogut et al. 2021; Procházková and Máša 2022). With their

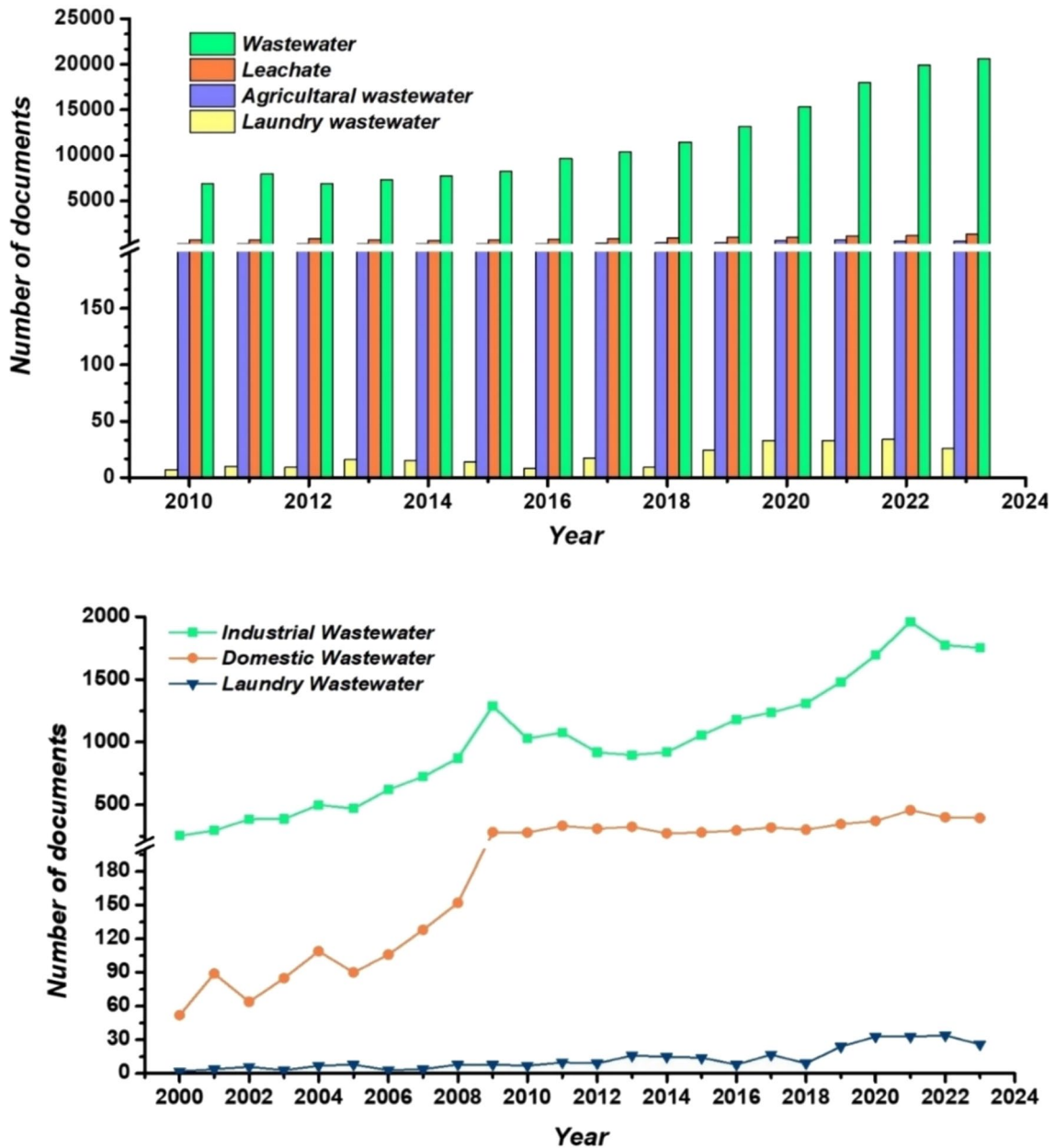


Fig. 2 Publications on wastewater, leachate, agricultural runoff, and laundry effluents from 2010 to 2023 (top). A comparative analysis of publication counts from 2000 to 2023 focusing on greywater generated by industrial, domestic, and laundry sector (bottom). Data Source: Scopus

wide range of services, including stain removal, mending and alterations, industrial laundries are an essential service for a variety of industries that need to keep their linen and other fabrics properly cleaned, safe, and presentable. Industrial laundries are little known to the general public. However, they played a crucial role in the fight against Covid-19 during the health crisis when they were used to gather and handle tainted laundry.

Industrial laundries, typically equipped with large-scale advanced machineries, target cleaning supplies, and proper techniques, are specialized facilities for washing,

drying, and pressing fabric items in large quantities. The automated machineries include washing machines for cleaning large amounts of linen, dryers for drying the washed items and pressing machines for finishing the linens (ironing, folding), and target cleaning supplies, which are specialized facilities for washing, drying, and pressing fabric items in large quantities, respectively. The washing machines are designed to deliver superior and efficient washing results, using advanced technologies and specialized programs that adapt to different types of fabrics and levels of soiling.

Industrial laundries are classified into two main categories according to their washing capacity: low-capacity laundries with less than 10 tons/day, which are the most common type (Procházková and Máša 2022; Lacalamita et al. 2023), and large laundries (10–50 tons/day). In Europe, industrial laundries are available as private and public commercial facilities, offering turnkey solutions to end users of linen. Most laundries offer basic laundry services (wet cleaning) and dry cleaning. In case of a heavy load of contaminants, the dual-phase washing process, which combines dry cleaning and water washing, is used.

Some of the items that can be processed in an industrial laundry include uniforms, industrial work wear, bedding, drapery, bathrobes, bath towels, and tablecloths. Dirty linen is classified into three main categories: those originating from industrial, chemical, automotive, paper, or metallurgical sectors; those from hospitals including from nursing homes and residential facilities; and those from hospitality sector such as hotels, restaurants, and cafeterias. These different types of laundry are not mixed and are treated separately as they require different washing programs based on the specific demands of the clients or having to comply with specific standards and regulations. For example, the hospitality sector (hotels, restaurants) requires top-level hygiene and efficiency for their bed linen, table linen, and guest linen. A high degree of cleanliness and hygiene is also required for hospital linen to make them free of germs and bacteria. In sectors such as food, it is also crucial to ensure proper hygiene and disinfection of linen (Fijan et al. 2005; Swartz et al. 2017; Sharma et al. 2019; Decker 2022).

It is important to note that in all cases, all wastewater from the different washes are sent to the treatment plant in the same storage tank. Indeed, there is no separation of wastewater, and the same treatment is carried out continuously (Lacalamita et al. 2023). However, the clothes to be treated are not the same, and the levels of dirt are also different. Therefore, washing programs do not use the same formulations. All this can impact the operation of the treatment plant (Sheth et al. 2017; Oteng-Pepurah et al. 2018; Santiago et al. 2021).

Operations

The general operation of industrial laundries consists of five main steps (Fig. 3): sorting, pre-spotting, washing (the main

step), drying, and finishing (ironing, folding). The laundry work is as follows: after collection from the customer site, sorting (this step depends on the soiled level, color, ownership, and fabric type), and counting, the laundry is sent to a washing tunnel consisting of several compartments, each with a given role. Soiled textiles undergo several successive washing stages: rinsing, wetting, pre-washing, pre-spotting, and rinsing, in which some of the dirty marks are identified and treated with typical substances, main washing including bleaching (if needed) and rinsing steps, and softening. The linen is then passed through a press for spinning before being sent to the dryers, and thereafter ironed and folded.

Chemical additives

Laundry wastewater contains a large amount of contaminants such as surfactants, microplastic fibers, oil, dust particles, pathogenic microorganisms, etc. (Kumar et al. 2022). Moreover, each step uses chemicals and products, among the best known of which are detergents, soaps, chlorinated bleaches, and perfumes (Scott and Jones 2000; Köhler 2006; Bajpai and Tyagi 2007; Yu et al. 2008; Steber and Wiebel 2012; Abd El-Gawad 2014; Zavala and Estrada 2016; Babajanzadeh et al. 2019; Abney et al. 2021; Khalid et al. 2022; Khan 2022; Kumar et al. 2022; Morris et al. 2022; Cüce et al. 2023). In reality, the list of chemicals or ‘ingredients’, which is the term used by the laundry sector, is more varied and complex. These ingredients are the main active agents and can be classified into fifteen categories (Table 2): surfactants, bleaches, alkalis, neutralizers, builders, anti-redeposition agents, fabric softeners, disinfectants, enzymes, solubilizers, optical brighteners, preservatives, foam regulators, fragrances, and corrosion inhibitors.

This classification is empirical, and there is no official list, and for example, alkalis, softeners, and anti-redeposition agents are sometimes considered as builders (Bajpai and Tyagi 2007; Ivanković and Hrenović 2010; Braga and Varesche 2014; Najim et al. 2022; Dimoglo et al. 2023). In addition, there are several terms used by manufacturers for the same ingredient (Table 2), and each can also play several roles, which can sometimes lead to confusion. In all cases, each ingredient has a special function. However, each product used is not a singular homogeneous species but rather a mixture of different types of chemicals (Köhler 2006). For example, the list of ingredients in a detergent is as follows

Fig. 3 The general operation of industrial laundries



Table 2 Ingredients used for washing, their functionalities, and examples of substances present in each formulation from the safety data sheet of manufacturers and published literature (Köhler 2006; Bajpai and Tyagi 2007; Yu et al. 2008; Scott and Jones 2000; Ivanković and Hrenović 2010; Steber and Wiebel 2012; Braga and Varesche 2014; Altenbaher et al. 2014; Zavala and Estrada 2016; Babajanzadeh et al. 2019; Abney et al. 2021; Khalid et al. 2022; Khan 2022; Kumar et al. 2022; Najim et al. 2022; Morris et al. 2022; Cüce et al. 2023; Dimoglo et al. 2023; Lacamita et al. 2023)

Ingredients	Description of function of washing	Examples of substances from the safety data sheet of manufacturers*
Surfactants		
Detergents	Reduce the surface tension of the water, which rapidly wets the linen, increase the contact between the linen to be cleaned and the water, and promote the penetration of water into the fibers, thus facilitating the removal of dirt and then its transfer/suspension in the water	Alkyl sulfates, alkyl ethoxylate sulfates, alkylbenzene sulfonates , alkyl aryl sulfonates, ethers of fatty alcohol, dodecylbenzene sulfonates, sodium cumene-sulfonates, fatty alcohol sulfonates, fatty alcohol ether sulfonates, alcohol ether sulfates, iso alkane, benzyl salicylate, <i>iso</i> -tridecanol, alcohol ethoxylates, (2-methoxy-methyl-ethoxy)-propanol, 3,7-dimethyl-1,6-octadien-3-ol, quaternary ammonium compounds, α -isomethyl-1-one, alkyl-polyglucosides, alkyl-polyglucosamides, alkyl-betaines, linalyl acetate, terpenes, glycerin, sodium carbonate
Surface active agents		
Cleaning agents		
Cleaning and degreasing agents	Used as mild antibacterial agents and in fabric softeners (cationic surfactants)	
Anionic surfactants		
Non-ionic surfactants		
Cationic surfactants		
Amphoteric surfactants		
Soap-free detergents		
Bleaches		
Bleach	Remove stains by oxidation (change in its oxidation state) and by cleavage of chemical bonds (stain degradation); resulting in the discolor of the stains; having also a disinfection role	Chlorine-based bleaches, sodium hypochlorite , calcium hypochlorite, percarbonates , sodium percarbonate , perborates, sodium perborate, peroxide-based products, hydrogen peroxide, peracetic acid, ethylenediaminetetraacetate, tetraacetyethylenediamine
Bleaching agents		
Active bleaches	Whitening and brightening of linen	
Active oxygen bleaches	Restore the luster of linen	
Bleaching activators	Clean and disinfect the washer	
Bleaching stabilizers		
Whitening agents		
Alkalis		
Alkaline agents	Increase the pH of wash water, which helps break down dirt and promotes the dissolution of oily dirt	Washing soda, sodium carbonate, soaps, sodium hydroxide, caustic soda, ammonium hydroxide, sodium phosphate, sodium bicarbonate, potassium silicate , sodium silicate
Soda-controlling agents	Facilitates the removal of dirt from the surface by repulsion of negative charges between those of water (which has increased thanks to pH) and those of the surface of the fabric (which are generally negative) to be washed	
Neutralizers	Help dissolve surfactant ingredients in liquid formulations, maintaining a uniform composition	
Neutralizing agents		
Reducing agents		
Neutralizers		
Neutralizing agents	Reduce or neutralize alkalinity	Sodium metabisulphite, formic acid , acetic acid, peracetic acid, alcohols, ethanol, propanol
Acids (sour)	Protect the fabric from potential damage (at high pH) and ensure its integrity	
Acid agents	Promote the dissolution of oily dirt	
Mild acids	Neutralize chlorine residue in clothes and remove other residual chemicals	
Reducing agents	Prevents the yellowing of fabrics and makes them softer and whiter	
Antichlors	Remove unpleasant odors, e.g., due to residual chlorine compounds	
Softeners	Treat delicate fabrics either to remove stains or to dry-clean them (solvents)	
Odor neutralizers	Prevent disruption of the physical properties of the detergent (alcohols)	
Deodorants		
Solvents		
Organic solvents		
Oils		

Table 2 (continued)

Ingredients	Description of function of washing	Examples of substances from the safety data sheet of manufacturers*
Builders	Various chemicals or additives which perform many specific functions	Sodium carbonate , sodium bicarbonate, perborates, perborates, sodium sulfate, sodium nitrate, sodium tri-phosphates , tetrasodium pyrophosphate, citrates, succinates, gluconates, tetraacetylenediamine, diethylenetriamine pentaacetic acid, triethanolamine, alcohols (ethanol, propanol), 2-butoxyethanol, (2-methoxy-methyl-ethoxy)-propanol, 2-methyl-1,3-propanediol, sodium disulfate, zeolites , polycarboxylates, silicones
Additives	Enhance the action of surfactants and improve laundering results	
Water-softening builders	Maintain the physical characteristics of surfactants during processing, storage, and consumer use	
Water softeners	Able to bind multiple molecules of water	
Alkalis	Remove or minimize the influence of interfering ions likely to act with surfactants; e.g., soften water by complexing calcium and magnesium ions, which favors the action of surfactants	
Anti-redeposition agents	Promote the dissolution of oily dirt and prevent their redeposition	
Activators	Provide alkalinity, which also assists in the dissolving of oily dirt	
Bleaching activators	Clean, degrease, and deodorize	
Cleaning agents	Enhance the bleaching effect at lower temperatures	
Degreasing agents	Protect the color	
Processing aids	Remove grease spots from fabrics and for the cleaning of light-colored fabrics (absorbents)	
Stabilizers	Maintain the characteristics of detergents during storage and consumer use (processing aids, solvents)	
Suppressors	Stabilize or prevent excessive sudsing	
Desiccants		
Solvents		
Precipitating agents		
Sequestrating agents		
Ion-exchangers		
Stiffeners		
Fillers		
Absorbents		
Anti-redeposition agents	Prevent redeposition of suspended dirt by increasing the negative charge on the fabric surface, so that the surface repels dirt because they are also negatively charged	Carboxymethylcellulose , phosphonates, polyvinyl pyrrolidone, polyethylene glycol, polyvinyl alcohol, sodium triphosphate, zeolites, sodium citrate, ethylenediaminetetraacetic acid (EDTA), polyacrylic acids
Auxiliary agents	Suppress or minimize the influence of interfering ions	
Additives	Soften water	
Anti-cling products		
Sequestering agents		
Chelating agents		
Complexing agents		
Ion-exchangers		
Dispersers		
Dispensing agents		
Fabric softeners	Soften and smooth textiles	Cationic surfactants , quaternary ammonium products, 3-iodo-2-propylbutylcarbamate, tocopherol
Antimicrobial agents	Reduce wrinkling, crinkling (greater ease of ironing), and static electricity (preventing the fabric from clinging)	
Sanitizers	Kill microorganisms (microbiocidal) or inhibit their growth (microbiostatic) on linen	Hydrogen peroxide, quaternary ammonium chlorides , sodium hypochlorite, triclocarban, triclosan, 5-chloro-2-methyl-2H-isothiazol-3-one, 2-methyl-2H-isothiazol-3-one, gluconic acid, alcohols, ethoxylated alcohols, acetic acid, cationic surfactants
Enzymes	Remove stains	Proteases (break down proteins), amylases (break down carbohydrates), lipases (break down fats), mannanases (for food-based stains), pectinases (for fruit-based stains)
Catalysts	Can smooth cotton fabrics	
Catalytic enzymes	Provide color and fabric care	
Auxiliary agents	Can help to remove fuzz and pills	

Table 2 (continued)

Ingredients	Description of function of washing	Examples of substances from the safety data sheet of manufacturers*
Solubilisers Hydrotropes	Assist in maintaining the pouring characteristics of liquid detergents by preventing gel and layer formation Maintain a uniform composition throughout the liquid detergent	Xylene sulfonates , cumene sulfonates, toluene sulfonates, glycols, glycol ether sulfates, urea
Optical brighteners Auxiliary agents	Give whiter and brighter appearance to linen, helping to keep them looking newer for longer Mask the appearance of an undesirable color such as the yellowing of fabric Introduce a complementary color	Aminotriazines , coumarins, stilbenes, phosphonates
Preservatives	Prevent liquid detergent spoilage during storage (by killing bacteria) Prevent the oxidation, discoloration, and bacterial growth on the linen	Glutaraldehyde , butylated hydroxytoluene, 2-bromo-2-nitropropane-1,3-diol (bronopol), ethylenediaminetetraacetic acid (EDTA)
Foam regulators	Inhibit the formation of foam during the washing cycle in order to increase the effectiveness of the wash Prevent the formation of foam by disrupting the surfactants at the air–water interface Cause foam bubbles to collapse by forming hydrophobic bridges across bubbles	Siloxane-based substances , paraffin-based products , soaps
Fragrances	Influence the perception of cleanliness Neutralize the inherent odor of detergent chemicals Can help create pleasant sensations during washing Inhibit corrosion of metallic washing machine parts	Petroleum-based substances
Corrosion inhibitors Additives		Sodium silicate

*in bold are common examples (each uses its own term to describe the substances)

(in order of importance by volume): builders, surfactants, bleach, brighteners, enzymes, fragrances, fabric softener, and others.

Several different chemicals are used in a mixture known as a formulation or 'recipe', each containing one or more active substances or ingredients and additives for well-defined roles. These formulations are generally ready-to-use commercial products prepared by chemical formulators. A laundry processing 6 tons of linen a day uses some thirty different formulations in its industrial process, which represents a significant number of chemical substances that are difficult to quantify (Lacalamita et al. 2023). This study also reported that the information regarding the precise content of organic and inorganic substances is limited.

Table 2 also gives examples of substances present in commercial formulations used in the laundry industrial process, which may be found in wastewater and treated water. These data have been extracted from manufacturers' technical data sheets and safety data sheets (where available) and from published literature (Bajpai and Tyagi 2007; Yu et al. 2008; Ivanković and Hrenović 2010; Steber and Wiebel 2012; Abd El-Gawad 2014; Braga and Varesche 2014; Zavala and Estrada 2016). In general, the chemical composition of the formulations is often not detailed in the data sheets of the products used, with only the role and function of the active agents being described.

Sometimes, certain formulations indicate biodegradability or the absence of target substances such as phosphates, alkylphenols, optical bleaching brighteners, metals, chlorine, fluorinated substances, and ethylenediaminetetraacetic acid or EDTA. However, although some commercial formulations are defined as biodegradable in agreement with their safety data sheet, numerous contaminants present in these formulations are a risk to human health and the integrity of the aquatic ecosystem because they are persistent and toxic to organisms (Steber and Wiebel 2012; Abd El-Gawad 2014; Altenbaher et al. 2014; Méndez-Hernández et al. 2022). Many of these substances have been debated for more than 20 years (Warne and Schifko 1999; Scott and Jones 2000; Köhler 2006; Ivanković and Hrenović 2010; Steber and Wiebel 2012; Abd El-Gawad 2014; Altenbaher et al. 2014; Rebello et al. 2014; Méndez-Hernández et al. 2022). Another important point concerns the fact that there are no specific regulations on the chemicals to be used, but simply recommendations for the use of biodegradable products.

Wastewater and discharge water quality

In any industrial process, the water taken for the process has been contaminated. Before considering any kind of treatment, it is necessary to know the volume of effluent to be treated, as well as the form, type, and concentration of contaminants (Morin-Crini and Crini 2017; Liu and Liptak

2000). The exact nature of the contamination in terms of origin and toxicity must also be known. Raw wastewater or effluent can be a non-uniform colored, malodorous mixture containing solids, including colloids, immiscible liquids such as oils, greases, hydrocarbons, and soluble substances of chemical or biological origin. The presence of such contaminations can also result in wastewater with high redox potential, high acidity or alkalinity, variable temperature, and pathogenicity problems. The chemical composition of laundry wastewater varies based on the sources, influenced by the washing method, the type of laundry, and the efficiency of the washing machine. The primary chemical constituents found in laundry wastewater include surfactants, bleaching agents, enzymes, optical brighteners, phosphates, dyes, fragrances, heavy metals, and microplastics. It is important to note that the concentrations of these chemicals typically diminish throughout the wastewater treatment process. Additionally, these levels may fluctuate over time due to a variety of factors, including dilution and degradation, seasonal variations, variations in treatment efficiency, and regulatory changes (Oteng-Peprah et al. 2018; Jayanto et al. 2021; Khajvand et al. 2022).

Water quality, including wastewater quality and discharge water quality, can then be defined by physical, chemical, and biological characteristics or analytical parameters (Liu and Liptak 2000; Noutsopoulos et al. 2018; Procházková and Máša 2022; Kumar et al. 2022; Aguilar-Torrejón et al. 2023). Physical parameters include temperature, turbidity, color, total dissolved solids, and total suspended solids. Solids can be classified into suspended and dissolved substances, as well as organic and inorganic fractions. A classic parameter for solids is the measurement of total dissolved solids and suspended solids, abbreviated as TDS and SS respectively. Chemical parameters associated with the organic content of industrial wastewater include pH, acidity, alkalinity, salinity, conductivity, dissolved oxygen (DO), chemical oxygen demand (COD), biological oxygen demand (BOD), total organic carbon (TOC), oil and grease, hydrocarbons, etc., and the measurement of target organic substances. Inorganic chemical parameters include metals, chlorides, fluorides, sulfates, forms of nitrogen, total phosphorus, etc. Bacteriological parameters include coliforms, specific pathogens, algae and viruses.

All laundry activities generate a tremendous amount of wastewater (Bering et al. 2017, 2018a, b; Oteng-Peprah 2018; Watinasih et al. 2019; Ho et al. 2021; Najim et al. 2022; Kumar et al. 2022; Lacalamita et al. 2023; Melián et al. 2023). Their composition and concentration vary according to the type of linen washed, the washing cycles, and the used products. As a result, the raw effluents are polycontaminated mixtures that can vary significantly in quality and quantity over time. There is a consensus, particularly in the literature, on the fact that these wastewaters

are characterized by high temperatures, basic pH values, high salinity, the presence of suspended solids (SS) including colloids, high values of COD and BOD, and the presence of organic and inorganic substances, such as metals, nitrogen and phosphorus peaks (Aonghusa and Gray 2002; Abd El-Gawad 2014; Braga and Varesche 2014; Dąbkowska 2017; Watiniasih et al. 2019; Najim et al. 2022).

Wastewater is also viscous, turbid, odorous, and sometimes colored. This is why the raw effluents are considered a potential primary pollution source because they contain an important amount of chemical impurities from the dirt from the washed textiles, along with the washing chemicals, which can be used in excess (Altenbaher et al. 2014; Bering et al. 2018a, b; Santiago et al. 2021; Kumar et al. 2022; Melián et al. 2023). Furthermore, there are currently no regulations governing this type of pollution for the industrial laundry sector.

The main parameters of water from laundries often described in the literature are: pH, SS, COD, and BOD (Braga and Varesche 2014; Lacalamita et al. 2023; Fountoulakis et al. 2016; Dąbkowska 2017). Sometimes, from an analytical point of view, a few target chemicals are described and studied. Among the chemical contaminants that may be in dissolved and particulate forms, many target substances, organic and mineral, have been identified, including linear alkylbenzene sulfonate, anionic, cationic and nonionic surfactants, lactate acid, malic acid, isobutyric acid, calcium, magnesium, phosphate, chloride, lead, zinc, iron, oil products, microplastics, nanoparticles, and microfibers. Anionic surfactants are of primary interest, for which examples of variations from 4.48 to 19.93 mg/L have been reported (Pandey et al. 2020).

However, the concentrations described vary greatly and it is very difficult to compare the data. For example, authors have registered the presence of substances of interest in laundry wastewater with the following concentrations: anionic surfactant (4.48–19.93 mg/L), calcium (16.94 ± 2.52 mg/L), and magnesium (11.54 ± 1.10 mg/L) (Pandey et al. 2020); detergent (463 mg/L), phosphorous (27.6 mg/L), lead 4.35 mg/L, and zinc 3.2 mg/L (Janpoor et al. 2011); anionic surfactant (6.5 mg/L), cationic surfactant (0.07 mg/L), and nonionic surfactant (275 mg/L) (Kaya and Dayanir 2020); anionic surfactant (7.51 mg/L), microplastics (15,804 MPs/L), and phosphate (13.8 mg/L) (Akarsu and Deniz 2021); total surfactants (9.42 ± 0.85 mg/L), phosphorous (3.25 ± 0.10 mg/L), and Fe (0.22 ± 0.12 mg/L) (Melián et al. 2023); linear alkylbenzene sulfonate (81 ± 82 mg/L), lactate acid (96 ± 93 mg/L), malic acid (85 ± 143 mg/L), isobutyric acid (48 ± 87 mg/L), phosphate (196 ± 136 mg/L), and chloride (89 ± 42) (Delforno et al. 2014); alkyl benzene sulfonate (19.68 mg/L) and oil products (3.70 mg/L) (Terechova et al. 2014).

Nonetheless, the analysis of all the data shows, that in terms of water treatment and engineering, the two main problems are the presence of particles and a strong organic load characterized by the COD and BOD parameters (Bering et al. 2011; Braga and Varesche 2014; Nicolaidis and Vyrides 2014; Sheth et al. 2017; Huang et al. 2019a, b; Furtado et al. 2020; Moharir et al. 2020; Ho et al. 2021; Jayanto et al. 2021; Alhinai 2022; Procházková and Máša 2022; Lacalamita et al. 2023). There is an urgent need for precise analytical data on the exact composition of laundry water (Braga and Varesche 2014; Noutsopoulos et al. 2018) and its temporal variability (Abney et al. 2021; Sheth et al. 2021; Lacalamita et al. 2023).

Regulations

Industrial laundries are increasingly being subjected to a variety of environmental regulations related to water consumption and wastewater management (Swartz et al. 2017; Khajvand et al. 2022; Procházková and Máša 2022; Konečná et al. 2023; Melián et al. 2023). Compliance with these regulations is necessary not only to avoid paying too many fines under the ‘polluter pays principle’ but also to maintain the company’s reputation.

This industrial sector is primarily a major consumer of water. As already stated, water consumption depends on the type of laundry, dirt, and the number of washing chemicals used and their concentration (Mozia et al. 2020). In Europe, water withdrawal is regulated (Directives EC n° 648/2004 and EC n° 907/2006; EC 2004, 2006). Each establishment is authorized to take and use a daily volume and an annual volume fixed in a regulatory framework, which will depend on the tonnage of their activity (Pedrazzani et al. 2012; Oteng-Peprah 2018; Mozia et al. 2020). Lacalamita et al. (2023) have recently reported that a French establishment that processes between 6 and 7 tons of linen per day is allowed to use a maximum volume of 250 m³ daily. In the case of this company, the amount of water used in the industrial process is between 100 and 120 m³, thus generating an identical volume of wastewater that must be treated. Bering et al. (2018a, b) previously reported that a Polish industrial laundry with a washing capacity of 80 tons of textiles per day generated nearly 600 m³ of polycontaminated wastewater daily.

Industrial laundry is an important producer of wastewater, which must be treated before discharge and, above all, must meet emission limit values for several water parameters and target substances. Industrial laundries encounter substantial challenges associated with the treatment of wastewater, which is characterized by a complex array of contaminants such as surfactants, fats, oils, phosphates, and suspended solids. These pollutants, primarily derived from the extensive utilization of detergents and cleaning agents, are difficult to manage due to their fluctuating concentrations and unique

chemical properties. Furthermore, the effectiveness of current wastewater treatment technologies is often inadequate for such a diverse range of pollutants, with surfactants presenting particular difficulties because of their high solubility and limited biodegradability. Additionally, industrial laundries face regulatory hurdles as specific guidelines tailored to laundry wastewater management are lacking. This deficiency forces these facilities to comply with a spectrum of general water quality standards, which can vary significantly across different jurisdictions. Moreover, the economic and operational burdens associated with the implementation of advanced treatment technologies represent another significant challenge (Swartz et al. 2017; Noutsopoulos et al. 2018; Oteng-Pepurah 2018; Ho et al. 2021; Singh et al. 2022; Konečná et al. 2023). These systems not only require substantial capital investment but also entail high operational costs, including those for energy consumption and ongoing maintenance, which must be balanced against the necessity for effective wastewater management.

However, only a few chemical analyses are taken into account (Directives EC n° 648/2004 and EC n° 907/2006; EC 2004, 2006). For detailed information on the quality parameters of laundry wastewater, it is necessary to refer to the national regulations or guidelines issued by the environmental agencies of each EU Member State (Melián et al. 2023). These documents generally provide specific limits and guidelines adapted to local conditions and wastewater treatment facilities. With the aim of achieving carbon neutrality in the EU by 2050, the European Green Deal recognizes wastewater treatment as a crucial area for environmental improvement, with particular emphasis on improving the chemical efficiency of the treatments used and encouraging innovation to find more virtuous and energy-efficient techniques. The European Green Deal presents both challenges and opportunities for the laundry industry. By embracing innovation, adopting sustainable practices and collaborating with stakeholders, the laundry industry can play a crucial role in achieving cleaner water and a more sustainable future (EC 2019, 2020a).

In France, with the progressive implementation of various European directives emanating from the 2000 Water Framework Directive and their transposition into French laws, a list of nine water parameters and 21 substances have been established for the laundry sector since 2007 (Table 3), which is part of the textile sector (French action called “Monitoring and Reduction of Substances Present in Water”; first circular dated 7 May, 2007). All these parameters and substances are thus characteristics of the waters of the laundry sector. From this list, each French laundry must monitor a certain number of parameters and substances declared in their prefectural degree of discharge at a given frequency. Since 2018, Table 2 provides a list of substances that has been supplemented with the following: aluminum, iron, six pesticides

(quinoxifen, aclonifen, bifenox, cybutryne, cypermethrin and heptachlor), hexabromocyclododecane, perfluorooctanesulfonic acid, and di(2-ethylhexyl)-phthalate (the *Journal Officiel de la République Française* of 6 October 2017). However, these substances are not systematically imposed on launderers, but they can be subject to ad hoc analyses (Lacalamita et al. 2023). In addition, there are currently no regulations governing the potential presence of microfibers in discharged water, except the measurement of SS.

Table 4 shows the legal maximum admissible level for different parameters and pollutants present in laundry discharge waters according to the regulations of different countries (France, Spain, Italy, Greece, Romania, Mexico, Indonesia, Oman, USA, and China). It can be seen from this table that there are differences in the standards for industrial wastewater discharge among different countries (Kavvalakis et al. 2016; Wang et al. 2021; Alhinai 2022; Violenta et al. 2022; Lacalamita et al. 2023, 2024; Melián et al. 2023). In Europe (France, Spain, Italy, Greece, Romania), there are specific restrictions on water parameters such as SS, COD, and BOD. The regulations are generally very stringent, reflecting the European Union’s overall strict environmental standards. In Asia (China, Indonesia), China has stricter regulations on nitrogen, phosphorus, and metals, especially in cities like Beijing, while Indonesia’s standards are relatively lenient but are tightening progressively. In the Americas (USA, Mexico), the standards in the USA vary by state, often focusing on reducing nutrients and toxic substances. Mexico is improving its standards but they are not as stringent as those in the USA.

In Canada, there is not a unified set of water quality standards, due to the variable guidelines and standards set by the various provinces. In the Middle East (Oman), there are particularly high standards for COD and metals, indicating a strict regulatory approach. However, these standards pose several challenges, such as technological limitations, especially in developing countries where facilities may lack advanced treatment technologies to meet stringent standards; economic constraints that make upgrading facilities costly and challenging, particularly for small and medium-sized enterprises; regulatory enforcement issues where lack of stringent enforcement leads to non-compliance; and knowledge gaps in awareness or expertise regarding the best available technologies for wastewater treatment. In future, as environmental awareness increases, regulations are likely to become more stringent, with lower permissible limits for pollutants and the establishment of standards for new parameters (Kavvalakis et al. 2016; Swartz et al. 2017; Oteng-Pepurah 2018; Ho et al. 2021; Alhinai 2022; Singh et al. 2022; Violenta et al. 2022; Wang et al. 2021; Konečná et al. 2023; Melián et al. 2023).

Most laundry effluent is discharged into municipal sewer systems and treated in local wastewater treatment

Table 3 French list of water parameters and substances established for the laundry sector. Source: *Journal Officiel de la République Française* of 6 October 2017; Annex VII for industrial

Category	Name	Abbreviation	Unit	Substance family
Water parameter	pH			
Water parameter	Temperature	T	°C	
Water parameter	Total suspended solids	SS	mg/L	
Water parameter	Chemical oxygen demand	COD	mg/L	
Water parameter	Biological oxygen demand	BOD	mg/L	
Water parameter	Total phosphorus		mg/L	
Water parameter	Total nitrogen		mg/L	
Water parameter	Total hydrocarbons		mg/L	
Water parameter	Adsorbable organic compounds	AOX	mg/L	
Substance	Total cadmium	Cd	mg/L or µg/L	Metals
Substance	Total chromium	Cr	mg/L or µg/L	Metals
Substance	Total copper	Cu	mg/L or µg/L	Metals
Substance	Total lead	Pb	mg/L or µg/L	Metals
Substance	Total mercury	Hg	mg/L or µg/L	Metals
Substance	Total nickel	Ni	mg/L or µg/L	Metals
Substance	Total zinc	Zn	mg/L or µg/L	Metals
Substance	Trichloroethylene		µg/L	VOCs ^a
Substance	Tetrachloroethylene		µg/L	VOCs ^a
Substance	Carbon tetrachloride		µg/L	VOCs ^a
Substance	Chloroform		µg/L	VOCs ^a
Substance	1,4,6-Trichlorophenol	TCP	µg/L	Phenols
Substance	2-Chlorophenol	2-CP	µg/L	Phenols
Substance	Nonylphenols	NPs	µg/L	Phenols
Substance	Anthracene		µg/L	PAHs ^b
Substance	Fluoranthene		µg/L	PAHs ^b
Substance	Naphthalene		µg/L	PAHs ^b
Substance	Brominated diphenyl ethers	BDEs ^c	µg/L	Organobromines
Substance	Tributyl-tin		µg/L	Organotins
Substance	Dibutyl-tin		µg/L	Organotins

^aVolatile organic compounds

^bPolycyclic aromatic hydrocarbons

^cSeven BDEs: 47, 99, 100, 154, 153, 183, and 209

facilities. However, the impact of these waters on the operation of urban wastewater treatment plants has been studied very little, and so has their toxicity. Currently, from a regulatory perspective, unlike other industrial sectors, ecotoxicological testing is not required to assess the toxicity of aqueous releases, even though biological contamination of water, whether bacterial, algal or fungal, is beginning to interest the authorities. As previously reported by Rebello et al. (2014), it is necessary to study the ecotoxicological impacts of the treated water on different bioindicators. The state-of-the-art shows that in this domain, there is very little data regarding water toxicity (Blasco et al. 2003; Paz et al. 2006; Steber and Wiebel 2012; Rebello et al. 2014; Kern et al. 2015; Silva et al. 2018; Mousavi and Khodadoust 2019; Badmus et al. 2021; Tomšič et al. 2023).

Environmental challenges

Nowadays, industrial laundries are effective in terms of water and energy use. Modern sustainable technologies in this field make it possible to significantly reduce costs as well as protect the environment. However, this industrial sector must constantly adapt as regulations evolve rapidly, particularly with the occurrence of the problem of emerging polluting substances present in environmental compartments, for example, perfluoroalkyl and polyfluoroalkyl substances (PFAS) and alkylphenols (APs) (Glüge et al. 2020; van der Veen et al. 2022), the presence of microfibers in treated waters (Belzagui and Gutiérrez-Bouzán 2022; Gutiérrez et al. 2022; Le et al. 2022; Sotiropoulou et al. 2023), and water scarcity and drought.

Table 4 Legal maximum admissible levels for different parameters and pollutants present in laundry discharge waters according to regulations of different countries

Parameter/Pollutant	France	Spain	Italy	Greece	Romania	Mexico	Indonesia	Oman	USA	China	Beijing (China)
pH	6.5–9	5.5–9.5	5–9.5	5–9	6.5–8.5	6.0–9.0	6.0–9.0	6–10	6.0–9.0	6.0–9.0	6.5–9.0
Temperature (°C)	30		30		40	35	±3 °C towards air temperature	43			35
SS (mg/L)	500	1000	200	250	350	72	100	1000	100	400	400
COD (mg/L)	1500	1600	500	1000	500	180	150	1500	250	500	500
BOD (mg/L)	500	1000	250	250	300		75	1000	30	300	300
Total phosphorus (mg/L)	10	20	10	10	5.0	18			1.0		8.0
Total nitrogen (mg/L)	100		15			30			10		70
Nitrates (mg/L)		30	30						10		
Total hydrocarbons (mg/L)	5	10	10								
AOX (mg/L)	1								0.02	8.0	1.0
Cr (III) (mg/L)	0.15					1.25			0.1		
Cr (VI) (mg/L)	0.1		0.2		0.2				0.05		
Total Cr (mg/L)					1.5						
Cu (mg/L)	0.4		0.4		0.2	5		1	1.3	2.0	1.0
Fe (mg/L)		10	4					5	1.0		5.0
Fe+Al (mg/L)	5										
Ni (mg/L)	0.2		4		1.0	3			0.1		
Zn (mg/L)	1.5		1.0		1.0	15			0.1	5.0	1.5
Total surfactants (mg/L)		6	4	10	25		5			20	15
Solvent extractable matter (mg/L)					30						
Nonylphenols (µg/L)	25								6.8		
References	Lacalamita et al. (2023, 2024)	Melián et al. (2023)	a	Kavvalakis et al. (2016)	b	c	Violenta et al. (2022)	Alhinai (2022)	USEPA (2004) Wang et al. (2021)	d	e

^aLegislative decree n° 152/06, Italy

^bRomanian Regulation NTPA-002/2002 (GD no. 188/2002; GD no. 352/2005) for effluents that undergo further treatment in the wastewater treatment plant of the city (<https://legislatie.just.ro/Public/DetaliuDocumentAfis/98310>)

^cThe maximum contaminant levels, expressed as a daily average for discharges into rivers, were extracted from the official website of this Mexican Environmental Regulation updated in 2021 (NOM-001-SEMARNAT-2021). The limit values were established depending on whether the discharge is released into rivers, lakes, marine areas, or soils (https://www.dof.gob.mx/nota_detalle.php?codigo=5645374&fecha=11/03/2022#gsc.tab=0)

^dThe Chinese laundry discharge water lacks industry standards, with local standards often being more stringent than national ones. In regions where local standards are established, they are implemented, such as DB11/307–2013. In areas without local standards, national standards, like GB8978–1996, are enforced. The data above is derived from the Chinese national wastewater standard GB8978–1996

^eThe data above is derived from the Beijing comprehensive water pollutant discharge standards (DB11/30–2013)

In addition to energy challenges (Konečná et al. 2023), industrial laundries face common environmental challenges regarding water resources (Swartz et al. 2017; Noutsopoulos et al. 2018; Oteng-Peprah 2018; Ho et al. 2021; Singh et al. 2022; Lacalamita et al. 2023), which can be summarized as follows:

- decrease the amount of water per ton of dirty laundry to be treated, also with the aim of making water use more efficient,
- use biodegradable, ecological, and safe cleaners and reagents for manipulators,
- produce water and waste that do not pose a risk to the health of employees and workers,
- improve the operation of the treatment plant on site,
- reduce the flow of pollution (in term of water parameters) and pollutants,
- recycle treated wastewater,
- determine the qualitative and quantitative chemical composition of discharge waters; on this point, in France, actions are currently being carried out to collect analytical information on the chemical substances released, in particular emerging substances of recent interest such as alkylphenols and fluorinated substances; these actions should make it possible to propose complementary treatment solutions for these target substances by 2028,
- start studying the presence of microfibers in wastewater and discharged waters and propose solutions to reduce this type of pollution (for the moment, there are no specific regulations on this subject, only recommendations).

Textiles are a major source of microparticle pollution in the aquatic environment (Vassilenko et al. 2019; Gavigan et al. 2020; Gaylarde et al. 2021; Belzagui and Gutiérrez-Bouzán 2022; Gutiérrez et al. 2022; Le et al. 2022; Bhat and Gani 2024). These textile microfibers coming from clothing are the main source of primary microplastics in the oceans, being the most common plastics found in aquatic animals (Gaylarde et al. 2021). Bhat and Gan (2024) studied the presence of microfibers (MFs) in the wastewater of Dhobi Ghats, a city in northern India, and compared it with microfiber pollution from commercial laundries. Concentrations of 3204 ± 270 MFs/L and $36,923 \pm 389$ MFs/L were recorded, respectively. In addition, microfibers smaller than $75 \mu\text{m}$ dominated in effluents from commercial laundries (around 53% of the total), and microfibers between 75 and $150 \mu\text{m}$ (around 52% of the total) were present in effluents from the Dhobi Ghats (Bhat and Gani 2024). The presence of these textile microfibers can negatively impact the aquatic ecosystem via several pathways, recently discussed by Le et al. (2022): for example, releasing toxic chemicals, acting as carriers of others contaminants, and blocking the digestive tract of aquatic organisms.

The presence of textile microfibers in water has been the subject of numerous comprehensive publications over the last decade (Prata 2018; Gatidou et al. 2019; Liu et al. 2019; Vassilenko et al. 2019; Sun et al. 2019; Bretas Alvim et al. 2020; Gavigan et al. 2020; Ramasamy and Subramanian 2021; Turan et al. 2021; Kwak et al. 2022; Le et al. 2022; Belzagui and Gutiérrez-Bouzán 2022; Allen et al. 2024; Arif et al. 2024). In Europe, this source of pollution as a global environmental problem is a key priority (EC 2018, 2020a). It is estimated that synthetic textiles are responsible for a global discharge of between 0.2 and 0.5 million tons of microplastics into the oceans each year (Sherrington 2016). Among anthropic activities, laundry activities are the most important source of microfibers in the aquatic environment (Hernandez et al. 2017; De Falco et al. 2019; Le et al. 2022). Indeed, the majority of microfibers from textiles are released the first few times textiles are washed. The factors causing the increase in microfiber release have been discussed (Hernandez et al. 2017; Issac and Kandasubramanian 2021; Periyasamy 2021). Since microfibers are not retained by washing machines, they are discharged with the washing machine wastewater. They are also emitted during textile manufacturing, garment wearing and end-of-life disposal, and are dispersed not only in water but also in air and soil. Much of the particulate matter, including microfibers and microplastics that end up in wastewater, is retained by wastewater treatment plants. However, a significant fraction is found in the aquatic environment (McIlwraith et al. 2019; Sun et al. 2019). Action must therefore be taken to eliminate this pollution, which has an impact on aquatic life and the degradation of biodiversity.

The important question is whether the problem should be dealt with upstream, that is, in the wastewater coming out of the laundry plants and the washing machines coming out of the homes, or downstream, that is, going into the urban treatment plants. A combination of both seems to be the solution (McIlwraith et al. 2019). The laundry industry is aware of the problem and is looking for solutions (Hernandez et al. 2017; Belzagui and Gutiérrez-Bouzán 2022; Le et al. 2022). Belzagui and Gutiérrez-Bouzán recently reviewed alternatives for the reduction of textile microfibers emission to water and discussed some viable solutions present on the market (Belzagui and Gutiérrez-Bouzán 2022). For example, new detergents and additives are being developed to reduce the generation of microfibers during washing. The use of new liquid detergents and fabric softeners can reduce the friction and damage to the fibers during washing. It is known that washing powders tend to induce more losses than liquid detergents, as they act as abrasives damaging the fibers. One solution could be to install new washing machines whose technologies promoting short washing cycles while using low temperatures, can reduce the rate of release of microfibers.

Other initiatives exist, as in France, where washing machine manufacturers are required to install microfiber filters in their machines from 2025, in order to reduce microfiber pollution. France is the first country in the world to legislate on this type of pollution (AGEC Law—*Loi anti-gaspillage pour une économie circulaire*; decree no. 2022–336 of 10 March 2022). This French law is anticipated to have significant environmental and economic impacts, stimulating innovation in washing machine technology and influencing global standards on mitigating pollution by textile microfibers. On this topic, Le et al. (2022) reported that small devices for capturing microfibers during household laundry activities are simple to use and affordable at the household level. This would require investment to develop adequate filtration systems for industrial washing machines (McIlwraith et al. 2019; Belzagui and Gutiérrez-Bouzán 2022).

Another important topic is the presence of so-called emergent substances in aqueous compartments (Peña-Guzmán et al. 2019; EC 2020b; Patel et al. 2020; ECHA 2022; Morin-Crini et al. 2022). For example, in Europe, the presence of PFAS substances in tap water and waters in general has become a priority (Glüge et al. 2020; van der Veen et al. 2022; Hubert et al. 2024). However, due to their chemical stability and poor degradation, these substances are poorly or even not eliminated by conventional water treatment methods (Buck et al. 2011). Because they have no carbon–carbon double bonds and no functional groups, they are also resistant to advanced oxidation processes. Innovation is therefore required to find removal solutions. Another alternative is to stop the usage of detergent formulations containing these substances. In any case, the laundry sector, like other industrial sectors, will have to take action to eliminate these emerging substances (Lassen et al. 2015). Since 2023, French companies, including those in the laundry sector, have had to monitor the presence of fluorinated substances in their effluent over a 6-month period. Eventually, based on the results of these campaigns, manufacturers will have to take action to eliminate PFAS, which are considered to be priority hazardous substances (the *Journal Officiel de la République Française* of 6 October 2017; French Ministry of Ecology and Solidarity).

Chemical substances in discharge water from the laundry industry

The review of the literature shows that numerous works mention a number of water parameters to characterize water from domestic and commercial laundry sources, with COD and BOD being the most widely considered (Bering et al. 2011; Braga and Varesche 2014; Sibil et al. 2014; Sheth et al. 2017; Noutsopoulos et al. 2018; Abney et al. 2021; Alhinai 2022; Kumar et al. 2022; Luo et al. 2022; Procházková and

Máša 2022). However, precise data concerning the pollution in terms of qualitative and quantitative fluctuations in discharge water from the laundry sector have seldom been reported. Indeed, among the approximately 100 recent publications examined, only two publications are available on the temporal variability of the chemical composition of laundry water (Braga and Varesche 2014; Lacalamita et al. 2023).

Braga and Varesche (2014) were the first to publish detailed information on the chemical composition of 30 laundry discharge waters taken over a one-month period. In particular, they identified and quantified 8 metals (Cd, Cr, Cu, Fe, Mn, Ni, Pb, and Zn), forms of nitrogen, phosphates, linear alkylbenzene sulfonates, 11 volatile fatty acids, and traditional water parameters (pH, SS, COD, BOD₅). The results showed that COD values were in the range of 622–4796 mg/L with an average of 1710 ± 968 mg/L. For SS, the values varied from 10 to 290 mg/L with an average of 80 ± 60 mg/L. Among the metals analyzed, iron and zinc were observed to have the highest concentrations in 100% of the samples. Linear alkylbenzene sulfonates were quantified in all samples, with concentrations between 12.2 and 1023 mg/L. Phosphates were detected in 93% of samples with an average of 94.6 mg/L. A wide variety of volatile fatty acids was found, the most common acids being propionic and isobutyric (100% of samples). Thirty-three xenobiotic organic molecules, including phthalates and nonylphenols, were identified but not quantified. The authors concluded that the main groups of chemicals were fragrances, preservatives, solvents, and some surfactants. Alhinai (2022) also pointed out the fact that metals, in particular copper, iron, and magnesium, were systematically identified and quantified in all the samples.

Only one paper in the literature, by Lacalamita et al. (2023), presents detailed analytical data on industrial laundry discharges and their temporal variability from both a qualitative and quantitative point of view. These authors investigated the chemical composition of the discharge water from a French laundry industry over a 12-month period for a total of 24 samples. The company processes 6000–7000 kg of laundry per day, uses 100–120 m³ of water per day and about thirty formulations in its industrial process, ranging from detergents to perfumes, including stain removers, disinfectants, bleaching agents, builders, enzymes, optical brighteners, and softeners. Over 160 chemical substances, including 27 metals, 58 volatile organic compounds, 16 polycyclic aromatic carbons, 7 polychlorobiphenyls, 9 alkylphenols, 22 chlorophenols, and 6 pesticides, were monitored. Their results showed that the discharged water presented both inorganic and organic polycontamination with a high degree of qualitative and quantitative variability but the water complied with the regulations in force. Of all monitored substances, only five metals (Al, Cu, Fe, Sr, and Zn), five minerals (P, Ca, K, Na, and S), and alkylphenols were

systematically present and quantifiable, while others, such as trichloromethane, brominated diphenyl ether, and fluorides, were occasionally found and quantified. Substances, such as chlorophenols, organo-tins, and pesticides were never identified.

The data of Lacalamita et al. (2023) also reported that, all the samples had quantifiable levels in COD and BOD₅. The average and standard deviation values were 835 ± 176 mg/L for COD and 445 ± 114 mg/L for BOD₅, indicating a biodegradability index of 2.0 ± 0.4 . In Europe, the water reference value for this index is 2.5 (Directive 91/271/CEE, 21-03-1994). The authors concluded that the main problem was the presence of a high organic load characterized by high BOD values. In another recent work (Lacalamita et al. 2024), the same group showed that BOD₂₁ values were particularly high compared to the initial COD, confirming the biodegradability of water. Laundry effluents were also rich in substances that are quickly biodegradable, which has been demonstrated by the values of the ratio between BOD₇ and BOD₅. However, a significant proportion of surfactants was not degraded, as shown by total organic carbon measurements and anionic surfactant analysis.

It needs to be noted that microfibers in industrial laundry wastewater represent a significant source of microplastic pollution, impacting aquatic ecosystems through physical harm and chemical release, affecting marine life and, potentially, human health. Research and regulatory efforts focus on developing effective filtration technologies, identifying key sources of microfiber emissions, and enhancing public and industry awareness towards sustainable practices. Technological innovations like advanced filters and improved textile materials aim to mitigate microfiber shedding. Although strides are being made in understanding and addressing microfiber pollution, comprehensive solutions and widespread regulatory measures are still needed to significantly reduce their environmental impact (Bretas Alvim et al. 2020; Ramasamy and Subramanian 2021; Turan et al. 2021; Kwak et al. 2022; Le et al. 2022; Belzagui and Gutiérrez-Bouzán 2022; Allen et al. 2024; Arif et al. 2024).

Treatment of wastewater from laundries

Wastewater treatment

Wastewater from the laundry sector is known to be difficult to treat through conventional processes (Seo et al. 2001; Hoinkis and Panten 2008). In general, to achieve the decontamination objectives, a combination of physical, chemical, and biological methods is used (Antonopoulou et al. 2013; Arvaniti and Fountoulakis 2021; Ho et al. 2021; Wang et al. 2021; Kumar et al. 2022). However, detailed information on the type of treatment is scarce in the open literature. It is a

very confidential sector (Lacalamita et al. 2023), and each laundry has its own processing method and know-how for the decontamination of its wastewater.

In general, a water treatment scheme has two main stages: the first is a primary treatment coupled with a pre-treatment, and the second is a purification or secondary treatment, which is the most important step to eliminate pollution. Pre-treatment, which can be carried out by mechanical, physical or chemical means, is used to remove solid particles, suspended substances, oils, and greases, as well as to oxidize and decomplex the substances. Wastewater is a mixture of organic and inorganic substances, in both insoluble and soluble forms, which interact strongly with each other, often under highly alkaline and saline conditions, and at variable temperatures. Techniques used include filtration, flotation, centrifugation, chemical oxidation, and chemical coagulation assisted by flocculation and separation stages (Matthaios et al. 2016; Huang et al. 2019a, 2019b; Mostafazadeh et al. 2019; Yaseen et al. 2019; Kelemen et al. 2020; Moharir et al. 2020; Ho et al. 2021; de Oliveira Cardoso Nascimento et al. 2021; Santiago et al. 2021; Khajvand et al. 2022; Kumar et al. 2022, 2023; Lacalamita et al. 2023, 2024; Melián et al. 2023; Vishali et al. 2023). The primary treatment stage is essential before considering secondary treatment, as particulate pollution and chemical complexation problems will hinder subsequent treatment, render it less effective, or damage treatment equipment.

Pre-treated effluent can then undergo secondary purification using the most appropriate chemical or biological techniques available to remove the dissolved organic load. Techniques used include chemical or electrochemical coagulation (electrocoagulation) alone or assisted by flocculation and separation steps (Ramcharan and Bissessur 2017; Dimoglo et al. 2019; Akarsu and Deniz 2021), chemical precipitation assisted by flocculation and filtration steps, biodegradation, and membrane bioreactor processes (Bering et al. 2017, 2018a, 2018b; Janus et al. 2017), the two latter methods also being assisted by subsequent separation steps between the sludge formed and the clarified/treated water. In some cases, there may be a final pH adjustment stage.

If it complies with regulations, the final water is sent either to the environment or to the treatment plant of the city where the laundry is located, the latter being the most frequent case in Europe. It is important to note that discharged water always presents mineral and organic contamination at variable concentrations, a relatively basic pH close to 8, high salinity, and the presence of colloids that are very difficult to eliminate completely. In certain cases, a final or tertiary treatment, using membrane filtration technique (Barambu et al. 2020; Kaya and Dayanir 2020; Kumar et al. 2022), for instance, can also be required to remove the remaining pollutants or the molecules produced during the secondary purification, e.g., the removal of salts produced

by the mineralization of organic matter. However, the use of tertiary treatment in Europe is limited, though it may be necessary in the future if new restrictions are applied. Figure 4 shows an example of a wastewater treatment system of a French laundry company, which treats between 100 and 120 m³ of wastewater per day using a range of physical, chemical, and biological techniques.

Tertiary technologies for laundry water treatment

In terms of pollution prevention, industrial laundries are looking for alternative or complementary solutions as regulations evolve. However, finding a tertiary water treatment process that is both efficient, viable and environmentally friendly is a real challenge for this sector, because their wastewater volumes are very high and, as mentioned above, even if they respect the regulations, these waters are often polycontaminated, complex, highly variable and very saline (Ho et al. 2021; Khalid et al. 2022). Tracking trace contaminants in variable waters is not easy. In addition, tertiary technology must be easily incorporated into existing treatment plants. It must also be energy-efficient and ideally allow recycling the treated water in the industrial process. So, the complementary process must take account not only of these technical and scientific questions but also of economic and ecological criteria.

The literature reports on several tertiary technologies for the post-decontamination of laundry water. These technologies can be divided into three main categories: conventional methods such as biodegradation and adsorption on activated

carbons; established decontamination techniques such as liquid–liquid extraction, ion-exchange assisted by filtration and adsorption steps, membrane filtration, electrochemical treatment (electro-coagulation, electro-flotation), membrane bioreactors, constructed wetlands, and evaporation assisted by adsorption post-treatment; and emerging techniques such as advanced oxidation and biosorption (Fountoulakis et al. 2016, 2017; Crini et al. 2019; Kora et al. 2020; Kotsia et al. 2020; Arvaniti and Fountoulakis 2021; Peter et al. 2021; Elgarahy et al. 2022; George et al. 2022; Morin-Crini et al. 2022; Tawfik et al. 2022; Anand et al. 2023; Balakrishnan et al. 2023; Farghali et al. 2023; Melián et al. 2023; Peng et al. 2023; Wu et al. 2023; Ruan et al. 2024; Sivanesan et al. 2024). Each treatment has its own constraints in terms of cost, feasibility, efficiency, practicability, reliability, environmental impact, sludge production, operation difficulty, pre-treatment requirements, and the formation of potentially toxic byproducts (Morin-Crini and Crini 2017; Crini and Lichtfouse 2019). Indeed, sustainability in industrial laundry wastewater treatment extends beyond the removal of conventional pollutants. By integrating water reuse into their objectives, for example by using membrane filtration and bioreactors, laundries can significantly reduce their environmental impact and move towards a circular economy. Despite current challenges, the benefits of sustainable practices, including cost savings and compliance with evolving regulations, highlight their promising potential for the future of the laundry industry (Morin-Crini et al. 2022).

Table 5 summarizes the advantages and disadvantages of different techniques using information published in the literature and provided by water engineering professionals. However, among the various tertiary treatment techniques currently cited, only a few are commonly employed by the laundry sector, for technological and economic reasons. Moreover, for the moment, regulations do not require a reversal to complementary treatment techniques. Nevertheless, the issues of reusing treated water, like that of raw water used and energy (Benis et al. 2021; Ho et al. 2021; Dimoglo et al. 2022; Khapra and Singh 2023; Konečná et al. 2023), is of growing interest to industry, as reuse has become a hotly debated social issue, leading to the use of tertiary water treatment techniques in the years to come.

Examples of potentially usable water treatment techniques

The evaluation of the water treatment techniques described in the previous section took into account criteria such as removal efficiency, operating and capital costs, complexity, feasibility, reliability, ease of operation, footprint, sludge production, environmental impact and scalability. This evaluation of different water treatment techniques was also based on the ability to treat the specific contaminants present

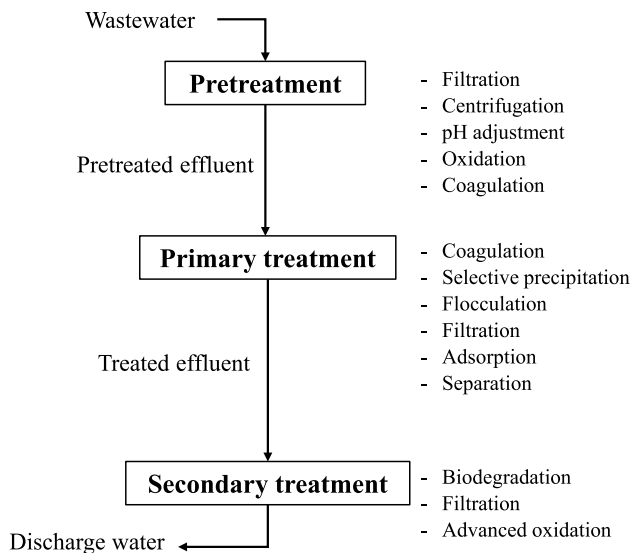


Fig. 4 Example of a wastewater treatment system of a French laundry company, which treats between 100 and 120 m³ of contaminated water per day using a range of physical, chemical, and biological techniques (source: G. Crini)

Table 5 Advantages and disadvantages of proposed tertiary techniques for the treatment of discharge water from the laundry sector

Technique	Advantages	Disadvantages	References
Adsorption on activated carbons	<p>Large range of carbons</p> <p>Efficient treatment when coupled to coagulation</p> <p>Ability to remove a large range of contaminants and color</p> <p>Synergistic effects enabling the simultaneous elimination of several pollutants/pollutions</p> <p>Very efficient for COD and detergent removal</p> <p>Excellent quality of the treated effluent</p> <p>Efficient for microfibers removal</p>	<p>Requires pre-treatment steps (coagulation, filtration)</p> <p>Rapid saturation and clogging of the reactors</p> <p>Elimination of the carbon</p> <p>Problem of the presence of several ions and high salinity on purification performance</p>	<p>Mostafazadeh et al. (2019)</p> <p>Veli et al. (2019)</p> <p>Moharir et al. (2020)</p> <p>Ho et al. (2021)</p> <p>Kumar et al. (2022)</p> <p>Atesci and Inan (2023)</p> <p>Khajvand et al. (2023)</p> <p>Nasir et al. (2024)</p>
Adsorption on other conventional adsorbents, e.g., alumina, zeolite, silica, carbonate rock	<p>Removes all types of contaminants</p> <p>Efficient for fluoride and detergent removal (alumina)</p> <p>Excellent quality of the treated effluent</p>	<p>Requires pre-treatment steps (coagulation, filtration)</p> <p>Rapid saturation and clogging of the reactors</p> <p>Elimination of the adsorbent</p> <p>Problem of the presence of several ions and high salinity on purification performance</p>	<p>Mostafazadeh et al. (2019)</p> <p>Veli et al. (2019)</p> <p>Kumar et al. (2022)</p> <p>Nasir et al. (2024)</p>
Biosorption on other non-conventional adsorbents (e.g., algae and bacteria mixtures)	<p>Green technologies using natural biosorbents (e.g., algae and bacteria mixtures)</p> <p>Removes all types of contaminants</p> <p>Efficient for phosphorus and nitrogen removal</p> <p>Excellent quality of the treated effluent</p> <p>Efficiency often independent of salinity</p>	<p>Laboratory scale; further work needs to be conducted</p> <p>Availability of biosorbents is an important limitation</p> <p>Requires pre-treatment steps (coagulation, filtration)</p> <p>Rapid saturation and clogging of the reactors</p> <p>Elimination of the biosorbent</p>	<p>Deresá et al. (2019)</p> <p>Yaseen et al. (2019)</p> <p>Pasaribu (2020)</p> <p>Ayu Haslija and Rabee (2020)</p> <p>Veli et al. (2021)</p> <p>Kumar et al. (2023)</p> <p>Rodzi et al. (2024)</p>
Bioprocesses	<p>Effective technologies using natural and biodegradable products (e.g., chitosan) which do not produce chemical residue in the water and create nonharmful, biodegradable sludge</p> <p>Bioprocesses are simple to apply, and are safe for the environment and human health</p> <p>The use of natural product is well accepted by the public</p> <p>Efficient for SS removal (biocoagulation), in particular for high-turbidity water</p> <p>Interesting effect on the reduction of COD and color, and also on the number of bacteria in water</p> <p>Mechanisms of coagulation and flocculation using bioproducts are well known</p> <p>Sludge generation reduction</p>	<p>Most researches are conducted on laboratory scale and application on real and large scaled treatment is challenging; further work needs to be conducted</p> <p>Extraction processes for raw materials (biocoagulants, bioflocculants) is complex and undeveloped yet</p> <p>Availability of the materials is an important limitation</p> <p>The choice and selection of the raw material giving the highest performance is difficult</p> <p>Performance is dependent on several parameters (pH, temperature, mixing, salinity) due to the occurrence of different mechanisms</p> <p>Operational costs are variable</p>	<p>Matthaios et al. (2016)</p> <p>de Oliveira Cardoso de Oliveira Cardoso Nascimento et al. (2021)</p> <p>Kasmudin et al. (2022)</p> <p>Vejar et al. (2024)</p>

Table 5 (continued)

Technique	Advantages	Disadvantages	References
Selective precipitation	<p>Significant reduction of COD, detergents, hydrocarbons, and metals</p> <p>Microfiber removal</p>	<p>Requires pre-treatment steps (oxidation)</p> <p>Requires adjunction of non-reusable chemicals</p> <p>Generates sludge</p> <p>Ineffective in removal of contaminants at low concentrations</p>	<p>Rott et al. (2017)</p> <p>Moharir et al. (2020)</p> <p>Maryani et al. (2021)</p> <p>Wang et al. (2021)</p> <p>Kumar et al. (2022)</p> <p>Li et al. (2022)</p> <p>Ciabatta et al. (2009)</p> <p>Wang et al. (2021)</p>
Dissolved air flotation	<p>Compact, modular, and adaptable technology with competitive capital costs and reduced site space requirements</p> <p>Automated system with reasonable costs (low maintenance and operation)</p> <p>Particularly suitable for waters containing low density particles, even those produced after chemical coagulation</p> <p>Obtaining high quality pretreated water from a particle point of view</p> <p>A proven and efficient clarification method for the removal of suspended matter and for pathogen removal, even at low temperature when sedimentation is not effective</p> <p>Little effect of temperature on performance</p> <p>Effect on color-causing organics, even at low temperature</p> <p>Interesting in the case of wastewater reuse as an end goal</p>	<p>Non-competitive (high energy costs) in the presence of high-density solids or waters with turbidities greater than 100 NTU</p> <p>Technique uses more energy than sedimentation</p> <p>Requires pre-treatment steps (pH control, coagulation, flocculation)</p> <p>Use of chemicals (coagulant aids, metal salts, polymers, flocculants) and materials (carbon powder) that are not recoverable</p> <p>Performance depends on the effectiveness of coagulation and flocculation</p> <p>Reduced performance at low water temperature or if the floc is fragile</p> <p>Little or no effect on dissolved pollution</p> <p>Sludge dewatering prior to discharge</p> <p>Requires post-treatment step (disinfection: e.g., by chlorination or ozonation) as a safety measure</p>	<p>Tripathi et al. (2013)</p> <p>Fang et al. (2016)</p> <p>Ciabatti et al. (2009)</p>
Ion-exchange	<p>Technological simple with established procedures</p> <p>Efficient treatment for metals and anions removal</p> <p>Excellent quality of the treated effluent</p> <p>Reduces water hardness</p>	<p>Requires pre-treatment steps (filtration, carbon adsorption)</p> <p>Initial cost of the resins</p> <p>Maintenance costs</p> <p>Rapid saturation and clogging of the reactors</p> <p>Problem of the presence of several ions and high salinity on purification performance</p>	<p>Tripathi et al. (2013)</p> <p>Fang et al. (2016)</p> <p>Ciabatti et al. (2009)</p>

Table 5 (continued)

Technique	Advantages	Disadvantages	References
Biodegradation			
Bioreactors	Economically attractive and treatment well accepted by the public	Efficiency depends on effluent concentration	Janus et al. (2017)
Membrane bioreactors	Efficient treatment for the elimination of biodegradable organic matter (COD and BOD) and forms of nitrogen	Requires management and maintenance of the microorganisms	Bering et al. (2017, 2018a, 2018b)
Aerobic bioreactors	Useful for removing target alkylbenzene sulfonates	Inefficient on non-degradable substances or when toxic compounds are present	Pérez-López et al. (2018)
Rotary biological contactors	Sustainable, green, and efficient technology in combination with a disinfection process (constructed wetlands)	Producing suspended solids and biomass and dissolve methane	de Faria et al. (2019)
Fluidized bed reactor	Effective method for greywater treatment (COD, BOD, SS, and surfactants removal) with treated water free of pathogenic content (membrane bioreactor)	Limitation on high COD content treatment	Siswoyo et al. (2019)
Anaerobic fluidized bed reactor	High BOD removal (biological activated sludge)	Problem of kinetics	Boano et al. (2020)
Sequencing batch bioreactors	Bioremediation is popular due to its long-term sustainability	Poor decolorization (biological activated sludge)	Kora et al. (2020)
Moving bed bioreactor	Effluent satisfies the international guidelines for indoor reuse (membrane bioreactor)	Requires adjunction of chemicals (anaerobic reactors)	Kotsia et al. (2020)
Biological activated sludge		Generates biological sludge and uncontrolled degradation products	Moharir et al. (2020)
Expanded granular sludge bed		Complexity of the micro-biological mechanisms	Arvaniti and Fountoulakis (2021)
Biofilters			Ho et al. (2021)
Bioremediation			Nicolaidis and Vyrides (2014)
Phytoremediation			Baihaqi et al. (2022)
Phycoremediation			Kumar et al. (2022)
			Violenta et al. (2022)
			Akhere and Chukwuka (2023)
			Rodzi et al. (2024)

Table 5 (continued)

Technique	Advantages	Disadvantages	References
Constructed wetlands			
Treatment wetlands	A mature ecological treatment with an initial investment cost substantially lower than of other conventional systems	Compared to conventional wastewater treatment systems, constructed wetlands generally require larger land areas	Fountoulakis et al. (2017)
Biofilters	Simplicity and low-cost of operation and maintenance	There is yet no consensus on the optimal design of systems	Arden and Ma (2018)
Bioremediation	Basic artificial systems using natural biogeochemical and physical processes in a given, unique and integrated ecosystem	There is still little information on their long-term performance	Tefa et al. (2018)
Phytoremediation	No requirement of continuous feeding and operation; need for minimal operational attention and skills; reliable and self-adjusting systems	Risk of unpleasant odors	Wahyudianto et al. (2019)
	The system can be combined with conventional treatment technologies to provide higher treatment efficiency	Need for a primary step to remove solids and particles	Kora et al. (2020)
	Ability to treat low strength wastewaters	Performance can be variable, depending on the type of systems uses, weather conditions, effluent composition (problems with recalcitrant organics) and operation (species involved)	Kotsia et al. (2020)
	Sustainable, economical and energy efficient technology and well accepted by the public	The biological components are always sensitive to toxic chemicals	Sharma et al. (2020)
	High efficiency for suspended colloids and organics	Some plants cannot tolerate complete submergence	Li et al. (2021)
		Problem of kinetics	Lutterbeck et al. (2022)
		The mechanisms of degradation are complex	Punyapwar and Mutnuri (2022)
		Initial cost of the equipment	Sotiropoulou et al. (2023)
		Cost of the maintenance (sacrificial electrodes)	Stefanatu et al. (2024)
Electrochemistry			
Electro-coagulation	Adapted to different pollutant loads	Requires addition of chemicals	Ge et al. (2004)
Electro-flotation	More efficient than traditional coagulation and flocculation methods; interesting methods due to their safety and environmentally friendly nature	Formation of sludge with filtering problems	Wang et al. (2009)
	Increases biodegradability very effective in removing SS and dissolved contaminants (electro-coagulation)	Cost of sludge treatment	Janpoor et al. (2011)
	In situ generation of active adsorbents and formation of gas causing flotation	Complex mechanisms	Ramcharan and Bissessur (2017)
	Efficient in removing microplastics (electro-flotation)		Dimiglo et al. (2019)
			Khor et al. (2020)
			Akarsu and Deniz (2021)
			Ho et al. (2021)
			Hu et al. (2021)
			Kumar et al. (2022)
			Luo et al. (2022)
			Huang et al. (2019a)
Bioelectrochemical systems			
Bioelectrochemical oxidation	Higher removal efficiencies compared to conventional treatment methods	Initial cost of the equipment	Huang et al. (2019a)
Bioelectrochemical degradation	Lower energy consumption as regards electro-chemistry processes	Require complex engineering and optimization due to the interplay of electrochemical processes and microbial metabolism	Srivastava et al. (2020)
Bioelectrochemical systems	Able to treat a diverse range of pollutants	Electrode fouling	Askari et al. (2021)
		Microbial competition	Ahmad et al. (2022)
		Scalability issue	Lutterbeck et al. (2022)
		Long term stability	Bashir et al. (2023)

Table 5 (continued)

Technique	Advantages	Disadvantages	References
Advanced oxidation processes			
Ozonation	Efficient in removing recalcitrant substances with disinfecting effect	Laboratory scale; studies are needed in terms of engineering design and modeling	Oliveira Schwaickhardt et al. (2017)
Catalytic ozonation	Mineralization of organics	Technical constraints (acidic pH, contact time, temperature); short lifetime of the generated ozone	Zotosso et al. (2017)
Photocatalytic ozonation	Little or no consumption of chemicals		Souza et al. (2019)
Photo-Fenton process	No production of sludge		Belén et al. (2020)
Photocatalysis	Rapid degradation	Excessive energy consumption	Furtado et al. (2020)
Electrochemical oxidation	Environmentally friendly and economically profitable (photo-Fenton process)	Economically non-viable for small and medium industries	Patil et al. (2020)
Cavitation		Ozone generation cost	Vishal et al. (2020)
Ultrasound		Cost and life of electrodes	Wahyuni (2020)
		pH-dependence and mass transfer limitations (ozonation)	Benis et al. (2021)
		Requires pretreatments (coagulation, flocculation, separation, pre-filtration)	García et al. (2021)
		Complete mineralization is not economical	Joseph et al. (2021)
		Formation of by-products	Ashari et al. (2023)
		Sludge formation	Šostar-Turk et al. (2005)
Membrane filtration			
Microfiltration	Simple, rapid, and highly efficient treatment (reverse osmosis)	High energy requirements	Ciabatta et al. (2009)
Cross-flow microfiltration	Cost-effective (gravity-driven membrane method)	Requires pretreatment steps (coagulation, flocculation, separation, pre-filtration)	Sumisha et al. (2015)
Ultrafiltration	Eliminates all types of contaminants (reverse osmosis)	Use of chemicals to protect membranes from deposit build-up by fouling, colloidal fouling and scaling by carbonates and sulphates	Manouchehri and Kargari (2017)
Reverse osmosis	Efficient for pathogen (e.g., <i>Escherichia coli</i>) removal	High investment and energy cost (membrane filtration)	Giagnorio et al. (2017)
	Highly efficient treatment (nanofiltration) when coupled to evaporation		Anita et al. (2019)
	Possible application as mobile treatment units		Chooobar et al. (2019)
	Treated water can be reused for laundering purposes (in some countries)		Collivignarelli et al. (2019)
			Huang et al. (2019a, 2019b)
			Mostafazadeh et al. (2019)
			Blad et al. (2020)
			Ho et al. (2021)
			Kogut et al. (2021)
			Kumar et al. (2022)
			Cahayani et al. (2024)

Table 5 (continued)

Technique	Advantages	Disadvantages	References
Evaporation	<p>A large choice of evaporators having diversity of sizes and shapes</p> <p>Effective at any levels of contamination, or when contamination is unknown and non-organic</p> <p>Interesting when there is not enough space to install a biological unit</p> <p>Drastic reduction of the volume of liquid waste which allows a saving in waste management</p> <p>Permits to achieve zero liquid discharge of wastewater</p> <p>Reuse of reclaimed water (high quality of the distillate)</p>	<p>The selection and design of an evaporator system must be carefully considered for each case: the choice can be difficult depending on the level of contamination, flow rate, and other conditions (temperature, pressure, residence time)</p> <p>The need for proper effluent characterization and its variability</p> <p>High investment and energy cost</p> <p>Post-treatment requirements (activated carbon step, filtration)</p>	<p>Haaz et al. (2019)</p> <p>Zhang et al. (2022)</p> <p>Valadez-Renteira et al. (2024)</p>

in industrial laundry wastewater, such as high salinity and variable contaminant loads. Ease of integration into existing treatment systems and the potential for water reuse were also taken into account. Based on this assessment, we have identified several water treatment techniques that can be used to treat laundry water.

Among the evaluated techniques, the following were deemed particularly auspicious:

- (i) Adsorption on activated carbons: This method is highly efficient, especially when combined with coagulation, for removing a broad range of contaminants, including color and detergents. It provides excellent water quality but requires pre-treatment and faces challenges such as rapid saturation and clogging (Atesci and Inan 2023; Nasir and Titah 2024).
- (ii) Membrane filtration techniques (e.g., reverse osmosis, ultrafiltration): These provide a high-efficiency solution for removing a wide array of contaminants and pathogens, making them suitable for reuse applications. However, they require significant pre-treatment and maintenance, and they are also energy-intensive (Huang et al. 2019b; Mostafazadeh et al. 2019; Bilad et al. 2020).
- (iii) Advanced oxidation processes (ozonation, photocatalysis): These are effective for the mineralization of organic contaminants and are environmentally friendly. They are particularly useful when chemical residue is a concern, although they can be costly and technologically demanding (Souza et al. 2019; Joseph et al. 2021).
- (iv) Membrane bioreactors: These are cost-effective and environmentally sustainable options that are well-accepted by the public. They are effective for organic matter removal but may be less effective against non-biodegradable substances (Bering 2018a, 2018b).
- (v) Constructed wetlands, which use natural processes, are cost-effective and environmentally friendly, offering good removal of nutrients, (biodegradable) organics, and pathogens, though they require significant land area (Tefa et al. 2018; Punyapwar and Mutnuri 2022; Violenta et al. 2022; Melián et al. 2023; Stefanatou et al. 2024).

Many studies point to the chemical efficiency of the proposed technologies but their economic viability is poorly addressed. Indeed, there is a lack of economic and financial data to compare different technologies (Humeau et al. 2011; Nicolaidis and Vyrides 2014; Punyapwar and Mutnuri 2022; Melián et al. 2023). Recently, the use of a combined system involving constructed wetlands and post-treatment with carbon adsorption was proposed to treat efficiently laundry wastewater to meet the required standards with a cost of 0.71 €/m³ (Melián et al. 2023). The same performance could

be obtained with photo-Fenton-based technology but with a cost of 6.72 €/m³. Some papers note that treatment such as membrane filtration and carbon adsorption may be economically viable, but no quantified data are available. Any study comparing wastewater treatment technologies must assess capital costs (equipment investment) and personnel, operational expenses (maintenance, operation) and long-term benefits such as energy savings and environmental impact. For example, membrane bioreactors typically have higher upfront costs, but lower operational expenses due to reduced chemical use and energy efficiency. Conversely, conventional activated sludge systems may have lower initial costs but higher ongoing operating expenses. Choosing the most cost-effective technology also requires consideration of local regulations, water quality objectives and life cycle costs to optimize investment and operational efficiency. It is therefore difficult to define a cost because it depends on several factors and the tertiary method chosen. In any case, before choosing a technique, laboratory tests and preliminary tests on industrial site must be carried out.

Conclusion

After a brief presentation of the activity of industrial laundry and their problems in terms of aqueous discharges, this comprehensive review has elucidated the multifaceted challenges and current practices associated with wastewater management in the industrial laundry sector. The review also listed chemical substances likely to be found in laundry industry wastewater, summarized environmental challenges for this industrial sector, and described data on the chemical composition of wastewater. A critical analysis of water quality and treatment methodologies revealed that laundry wastewater was inherently complex due to its variable chemical composition and the presence of organic and inorganic contaminants including surfactants and metals. These contaminants pose significant environmental risks, necessitating advanced treatment strategies. The main facts and observations are as follows: an ever-expanding industrial sector, with ever-increasing water requirements; abundant use of chemical substances; increasingly stringent discharge regulations; lack of chemical and biological knowledge of aqueous discharges; little information on water treatment plants; an industrial desire to withdraw less water and improve discharge quality, with the aim of achieving zero discharge of pollutants.

The laundry sector is required to implement actions to reduce the flux of certain substances and water parameters discharged into the environment, by 2028 in Europe, for example. In addition, increasingly restrictive environmental standards associated with high water charges on water consumption and waste streams force industrial

laundries to reuse or recycle treated water by implementing additional treatments. Anyway, before considering any additional treatment actions, qualitative and quantitative knowledge of discharges and their temporal variability is essential. Regrettably, as outlined in this review, the available data on this aspect remain incomplete. The review highlighted the effectiveness of various treatment techniques, from conventional physical and chemical processes to more sophisticated biological and tertiary treatments. For the first time, the review gave an example of a general scheme of wastewater treatment, and presented advantages and disadvantages of water treatment methods that can be used as secondary treatment in current plants, or tertiary treatment, i.e., complementary to existing treatment. Among the numerous methods available to treat discharge water from the laundry industry, membrane filtration and membrane bioreactors combined with disinfection step are frequently lauded for their superior efficiency and technical feasibility, as well as their capability to facilitate water reuse. However, it must be taken into account in operating costs that these methods are also energy intensive. Advanced oxidation processes, membrane filtration, and bioelectrochemical technologies also show promise for enhancing pollutant removal efficiency. However, the practical implementation of these innovative methods encounters obstacles such as high operational costs, technical complexity, and scalability issues.

Future research should focus on optimizing these advanced treatment methods to improve their cost-effectiveness and ease of integration into existing facilities with compact and simple equipment. Objectives should also focus on the targeted elimination of microplastics and emerging contaminants. Additionally, there is a pressing need for more stringent and specific regulatory frameworks tailored to the unique challenges of laundry wastewater. Such regulations would encourage the adoption of best practices and technologies, ultimately leading to more sustainable water management in the sector. Moreover, the ongoing development and refinement of treatment technologies must be paralleled by enhanced regulatory measures and industry standards. This will ensure that the treatment processes not only comply with environmental regulations but also contribute to the broader goal of water sustainability. The findings from this review urge policymakers, industry stakeholders, and researchers to collaborate more closely to address the critical issues of water quality and treatment efficacy in the industrial laundry sector. Finally, this review serves as a call to action for continuous innovation and stringent regulation in laundry wastewater management. By advancing our understanding and application of effective treatment technologies, we can better protect our water resources and promote a more sustainable and environmentally responsible industry.

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Declarations

Conflict of interest The authors declare no competing interests. EL declares that he is Editor of Environmental Chemistry Letters.

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