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Environmental challenges of disposable wipes: causes, impacts, and sustainable solutions

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The global surge in disposable wipes consumption has revolutionized hygiene and cleaning practices, but has introduced significant, often overlooked, environmental challenges. Despite growing awareness, the improper disposal of wipes, many of which are incorrectly marketed as flushable or biodegradable, continues to contribute to sewer blockages, persistent microplastic pollution, and increasing landfill burdens. Misleading labeling, incorporation of synthetic fibers, and inadequate structural disintegration have all intensified these environmental risks. This review explores how the current design and material composition of disposable wipes contribute to these environmental challenges. Analyzing the whole manufacturing chain—from raw material selection to bonding methods—identifies critical factors that affect flushability, degradability, and microfiber shedding. The presence of non-biodegradable synthetic polymers and the physical robustness of wipe structures due to web formation and bonding have been shown to impede environmental breakdown and proper disintegration. Aiming to develop sustainable wipes to mitigate these problems, several technical challenges were introduced within existing technology, and at the same time, viable solutions were proposed. Utilizing fully biodegradable, naturally sourced, or regenerated fibers, engineering fiber geometry, replacing conventional synthetic binders, and optimizing manufacturing processes were highlighted as promising strategies for developing sustainable wipes.

Sustainability spotlight

This study investigates the environmental impact of wet wipe disposal by examining the polymeric materials and processing methods used in their production. Key chemical, physical, and functional parameters contributing to sustainability concerns are identified. Strategies to optimize these factors based on end-use are discussed. The paper proposes alternative materials and eco-friendly manufacturing approaches, including sustainable raw materials, bonding techniques, wiping solutions, and performance testing standards to improve degradability and flushability without compromising functionality. Overall, this review provides a comprehensive framework for developing sustainably manufactured wet wipes.

1. Introduction

The global market for nonwoven wipes is rapidly growing, with a massive portion being disposable and single-use.[1] In 2022, the wet wipes global market was valued at \$27.54 billion and is expected to reach USD 48.47 billion by 2030, with a growth rate of 7.32% each year.[2] They are widely used for including, but not limited to, personal hygiene, skincare, healthcare, industrial, household cleaning, *etc.*[3–6] According to the Smithers report in 2024, the global consumption of wipes was equivalent to 1.7 million tons.[7] Such single-use wipes are often disposed of improperly, becoming a rising concern.

Increased usage, however, comes with significant environmental and plumbing challenges, especially from non-flushable and non-biodegradable wipes varieties.[8,9] Many consumers incorrectly assume that all wipes labeled “flushable” will disintegrate like toilet paper, leading to costly repairs for municipalities. Most of the wipes are disposed of in household trash and end up in soil or landfills, and take hundreds of years to decompose.[1]

Disposal of wipes into different environments comes with costs and long-term consequences. Flushing non-flushable wipes has caused sewer blockages, fatbergs, and environmental pollution.[10] Big cities like New York and London must spend 18–19 million dollars[11,12] to fix the fatberg, while in the US, this estimated expenditure is 1 billion dollars per year.[13] Several other cities in Europe, Asia, and Australia, including

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Berlin, Sydney, Melbourne, and parts of China and Spain, are also experiencing sewer blockages and environmental leaks as a result of wet wipe disposal.[14–17] Additionally most of the wipes are not degradable.[18] Even though labeled as biodegradable, many wipes contain cellulose-based fibers blended with low-degradable synthetic fibers.[19,20] These materials do not fully degrade in environmental conditions, leading to persistent microplastics, health hazards, and increased waste management challenges.[1,21,22] Degradability of wipes is the biggest concern because, either it is discarded to landfill, soil, or aquatic environment, it needs to be degraded. Both dry and wet wipes release microplastics, and on average, 1 gram of wipe can release 56 microfibers,[23] where non-biodegradable polypropylene and polyester terephthalate were found at the highest amount in soil and surface water.[24]

The manufacturing techniques and structural variables of nonwoven wipes contribute to these problems. Optimization of variables is so critical that one feature may hinder the functionality of other features. For example, bio-based raw materials might solve the degradability issues.[25] However, the length of those fibers might disturb the flushability.[26] In fact, each stage of manufacturing, such as the properties of selected raw materials, web formation, and bonding techniques, is influential in addressing these issues[27,28] and needs to be carefully considered.

Therefore, understanding the effect of processing variations on structural characteristics is crucial to mitigate these growing problems by designing sustainable wipes. We consider sustainable wipes to be wipes that will cause rapid structural disintegration when exposed to flush, and constituents will be degradable regardless of the disposal routes. In this review, we discussed the manufacturing procedure of wipes and their common disposal routes. Following that, we depicted how such disposal routes cause different issues and identified the potential factors behind such problems. By doing that, potential technical solutions were critically evaluated and proposed to develop sustainable nonwoven wipes.

2. Overview of wipes

Wipes are fibrous structures typically composed of nonwoven materials or composite sheets designed to provide effective cleaning, hygiene, or disinfection solutions. They are commonly available in either pre-moistened or dry forms and are disposable. According to the Association of the Nonwoven Fabrics Industry (INDA), wipes are lightweight, durable, cost-efficient, and easy-to-use nonwoven products tailored to meet specific cleaning needs.

Nonwoven technology is crucial in producing the most disposable and affordable products. Its high production efficiency ensures that nonwoven products remain cost competitive. Most wipes available in the market today are nonwoven. Nonwovens are fibrous webs created directly from resins or fibers, requiring bonding processes instead of traditional weaving or knitting methods. This technology involves four primary steps: (1) selecting raw materials, (2) forming the web, (3) bonding, and (4) finishing. A variety of raw polymers, including natural, synthetic, and blends of those, are used as raw materials to manufacture wipes. In addition, several techniques are employed to develop the web and subsequent bonding processes. Steps 1 and 4 are tailored to achieve the desired aesthetic and functional properties, while steps 2 and 3 focus on ensuring structural stability. This section will highlight the standard industrial manufacturing process for wipes.

2.1 Nonwoven wipes manufacturing process

Considering the end use, wipe manufacturers start by selecting the appropriate raw materials conducive to offering the required properties. For example, wipes intended to absorb moisture or liquids require hydrophilic materials, whereas wipes for cleaning oily surfaces prefer hydrophobic materials. Natural and regenerated polymers sourced from wood pulp, cotton, bast fibers, or cellulosic derivatives derived from plants, along with synthetic polymers such as polyester terephthalate, polypropylene, polyethylene, nylon, poly lactic acid, and polyhydroxybutyrate, are seen to be used as raw materials. Table 1 demonstrates potential polymeric materials used for wipes production. Sometimes, natural and synthetic polymers are blended to enhance processing conditions and properties.[29] Depending on their properties, such polymers are spun into staples, filaments, or converted into molten forms before web formation. Physical properties and associated costs sometimes determine the web formation process. For example, dry laid and wet laid processes[30] are used to make webs from natural fibers and pulp, respectively. Dry laid can be classified into carding and air laid processes. Webs made from carding have higher strength in the machine direction, where air laid webs offer soft, fluffy structure and isotropic strength due to random orientation distribution.[31,32]

Synthetic polymers can also be melted to make webs by the spun-laid process. Spunbond and meltblown both belong to the spun-laid process. Several synthetic polymers, ranging from polyolefins, polyesters, polyamides, polyurethanes, *etc.*, are used for spun-laid processes,[47,48] which are melted and extruded; however, spun-bond webs require an additional bonding technique, where meltblown webs are bonded by the molten extruded polymers upon solidification. Although the melting of polymers requires additional energy cost, the low price of synthetic polymers and high production capacity make the spunbond process more efficient for nonwoven production.[48]

Bonding is used in nonwoven wipes to provide structural integrity and strength, ensuring the wipes remain intact during use. Several mechanical, thermal, and chemical bonding techniques bind fibers on the web. Mechanical bonding includes hydroentangling and needle-punching, where hydroentangling uses high-pressure water jets, while needle-punching uses barbed needles[49] to interlock fibers. Thermal bonding involves heat and pressure by calendar roller or through air to melt binder polymers or bicomponent fibers in specific areas in the nonwoven wipes.[50] Polyethylene, polyvinyl acetate, ethylene-vinyl acetate, polypropylene, carboxymethyl cellulose, chitosan, polylactic acid, *etc.* are used as binder polymers.[51,52]

Table 1 A list of commercial wipes patented by well-known companies, highlighting common polymeric raw materials used for wipes manufacturing

Patent number	Assignee	Materials	Ref.
WO2006044295A1	Procter & Gambel	100% Thermoplastic bicomponent	33
US20060068673A1	PGI Polymer Inc.	PET/PP	34
US4808467	Fiberweb North America Inc.	Blend of synthetic and wood pulp	35
US4578414	The Dow Chemical Company	Polyolefin	36
US4837078	Hercules Incorporated	Natural/polyolefin	37
US 8501647B2	Buckeye Technologies Inc.	Natural/synthetic	38
US9103057B2	Suominen Corporation	Natural/PLA	39
US11767642B2	PGI Polymer Inc.	Natural/synthetic	40
EP3199682B1	Glatfelter Corp.	Cellulose/bicomponent	41
US3561447A	Fiber Technology Corp.	PVA	42
US20210177744A1	Shannon E. Klingman	Synthetic sheet with natural core	43
US2025/0146197A1	Glatfelter Holdings Switzerland AG	Cellulosic-based fibers	44
US20040013859A1	Suominen Oyj	Natural and manmade cellulose	45
US10973384B2	Magnera Corp.	Cellulose/synthetic blend	46

Choice of web formation and bonding type determines the physical properties of nonwoven products. Researches produced wipes using a wood pulp/lyocell blend through the wet laid web process, followed by hydroentangling bonding.[30] The resultant product exhibited lower wet strength in the cross-direction compared to the web direction.[30] The spun-laid process typically exhibits higher strength in both the machine and cross directions, with higher production efficiency compared to the dry-laid process. Some techniques have been developed that combine web formation and bonding techniques for specific purposes. For example, spun lace involves entangling a nonwoven web of loose fiber webs made by a dry-laid or wetlaid process on a porous belt or forming wire, by subjecting the fibers to multiple rows of fine, high-pressure water jets.[53] It is also called wet lace or air lace, which means the web is made by wetlaid or air laid, respectively, followed by the hydroentangling process.[30,53] Polymers such as polypropylene and cellulose fibers, derived from wood pulp, are combined through an air-laid process to create conform, which is unique in its development. Co-form produces soft, absorbent material with good strength properties. It is particularly well-suited for wipes that require a balance of absorbency and strength. Co-form is widely used in baby wipes and other personal care applications.

Fig. 1 shows the general wipes manufacturing process starting from material selection up to the bonding process. The last stage of the wipes is the finishing part. Based on the end use, these wipes are pre-moistened into various solvents by impregnation, coating, padding, *etc.* For example, solvents used for disinfecting wipes might be quaternary ammonium chloride, hydrogen peroxide, ethyl alcohol, *etc.*[54] Solvents for cleaning wipes are mostly deionized H_2O, deionized H_2O–alcohol mixture, butyl acetate, a deionized H_2O–surfactant mixture, or acetone. Besides solvents, dry particles such as super absorbent polymers, anti-grease, odor absorbent disinfectants, surfactants, antimicrobials, antioxidants, and preservatives are also impregnated, coated, or sprayed onto the wipes to meet the requirements.[55,56]

2.2 Classification of wipes and disposal routes

Wipes can be classified in several ways, mostly based on end use or functionality. For example, personal care wipes are designed for direct use on the skin for cleansing, hygiene, and cosmetic purposes. These include baby wipes, facial cleansing wipes, makeup removal wipes, feminine hygiene wipes, and moist toilet tissues. The substrates for personal care wipes are typically blends of cellulosic and synthetic fibers.[5] Household wipes are intended for cleaning and disinfecting surfaces within the home environment. In addition, these wipes are used for tasks such as kitchen and bathroom cleaning, dusting, and general surface disinfection.

Industrial wipes are commonly made from nonwoven fabrics, which may include blends of viscose, polyester, polypropylene, and sometimes wood pulp to balance absorbency, strength, and cost.[64] Table 2 shows different kinds of wipes and their constituent materials. Household wipes have disinfectants or detergents impregnated in them, while personal care wipes contain skin-compatible cleansing agents, water, or moisturizer.[5] Industrial and healthcare wipes are specialized products used for cleaning, disinfecting, or sanitizing in settings with high hygiene requirements, such as hospitals, laboratories, and manufacturing facilities.

Wipes have numerous uses, ranging from personal hygiene and household cleaning to industrial applications; however, improper disposal still poses a significant threat to the environment and infrastructure. Based on the disposability, wipes can be further classified into either flushable or non-flushable wipes. Any wipes can fall under these categories. For example, baby wipes, or make up removing wipes can be both flushable or non-flushable depending on its compositions and how they are made. Fig. 2 illustrates the classification of wipes and disposal routes. Based on the classification, the proper disposal routes should be separated to avoid several environmental consequences.

Single-use non-flushable wipes are suggested to dispose of in the garbage bin,[68] which ends up in the soil[69] and landfill.[69,70] Some of those might be composted or incinerated by the municipal waste management system (MWMS) but the amount

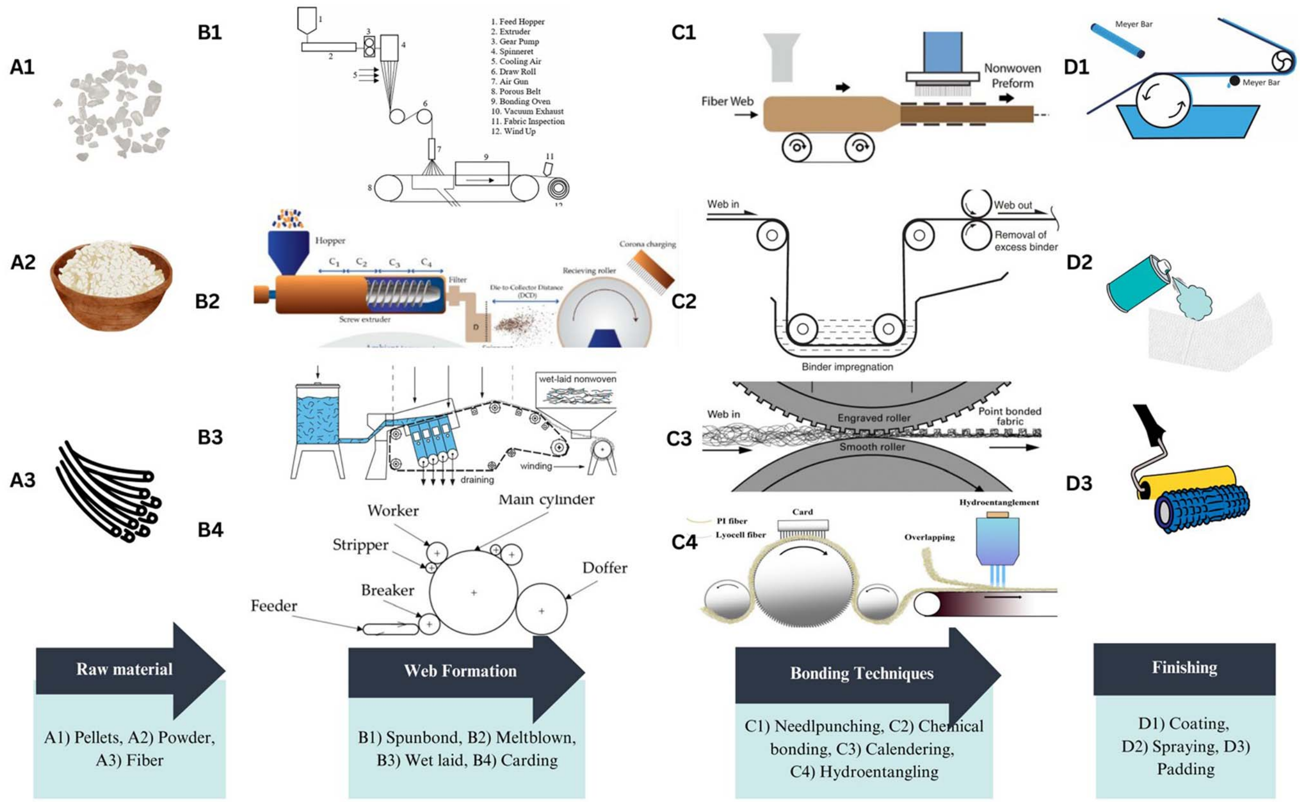

Fig. 1 A graphical representation of the wipe manufacturing process from different forms of raw materials, pellets (A1) (created with Canva), powder (A2) (created with Canva), staple fiber (A3) (created with Canva). Nonwoven webs are made from (A1) and (A2) type raw materials using spunbond (B1). Reproduced with permission from ref. 48. Copyright 2022, Elsevier Ltd and Meltblown (B2). Published under the CC-BY License.[57] Copyright 2023, The author. Published by MDPI. At the same time, wetlaid (B3). Published under the CC-BY License.[58] Copyright 2023, The Authors. Published by Elsevier Ltd and carding (B4). Published under the CC-BY License.[59] Copyright 2025, The authors. Published by MDPI, process utilizes pulp and staple fibers before securing the structure by bonding processes such as needle-punching (C1). Published under the CC-BY License.[60] Copyright 2021, The Author(s), Published by Springer Nature Switzerland AG 2021 L. A. E, chemical (C2). Reproduced with permission from ref. 61. Copyright 2009, Woodhead Publishing Limited, thermal (C3) Reproduced with permission from ref. 62. Copyright 2022, Elsevier Ltd, and hydroentangling (C4) Published under the CC-BY License.[63] Copyright 2024, The authors. Published by MDPI. Wetting liquid for functional purposes is loaded in wipes by different finishing processes, such as coating (D1). Reproduced with permission from ref. 56. Copyright 2022, Elsevier Ltd, spraying (D2) (created with Canva), padding (D3) (created with Canva).

Table 2 Different types of wipes with their constituent materials and properties

Types of wipes	Raw materials	Wiping chemicals	Characteristics	Ref.
Personal Care	Viscose, lyocell, cotton, polyester, polypropylene	Purified water, mild surfactants, fragrance, moisturizers, skin-compatible additives, *etc.*	Soft, highly absorbent, and should not cause skin irritation	5
Household	Polyester, polypropylene, wood pulp, cotton	Quaternary ammonium compounds, hydrogen peroxide, hypochlorite, *etc.*	Strong for wiping, absorbent, and should remove dirt	54 and 65
Industrial	Polyester, polypropylene, viscose, lyocell, wood pulp, composites	Stronger solvent for degreasing and removing paints, surfactants, strong oxidizers, Sodium hypochlorite, *etc.*	Tough, durable, solvent-resistant, used for grease or oil removal	66
Healthcare	Polyester, polypropylene, viscose, lyocell, wood pulp, composites	Alcohol, Benzalkonium chloride, sodium hypochlorite, *etc.*	Antibacterial, high absorbency, lint-free, suitable for disinfection	67

is very insignificant. In China only 0.2% of all domestic waste are wipes which are incinerated by MWMS while rest of the wipes leaked into environment due to direct disposal.[70] Long-lasting structures of constituent synthetic polymers or blends used in household cleaning wipes, including wet wipes and facial wipes, make them persistent, resisting breakdown in

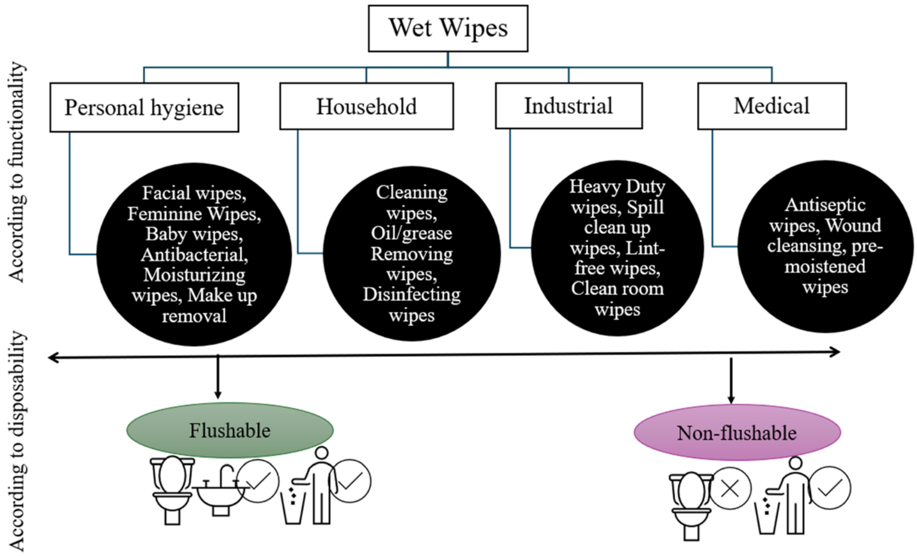

Fig. 2 Classification of wipes commonly used in daily life (created with Canva).

natural settings. Many cleaning wipes contain disinfectants, such as quaternary ammonium compounds (QACs) or hydrogen peroxide, making them effective against bacteria. However, these chemicals can be potentially harmful if they enter water systems,[65] and their disposal requires further careful consideration. Beyond personal and household use, industrial wipes, which include cleanroom wipes and heavy-duty wipes used in factories, commercial spaces, laboratories, and construction sites, pose problems due to their absorbent nature and exposure to hazardous chemicals, oils, and solvents. To prevent contaminating soil and water supplies, these materials must be disposed of with greater care and are frequently treated as hazardous waste.[1] To minimize waste, some multipurpose industrial wipes can be professionally cleaned and reused.

Furthermore, to ensure public health safety, medical and disinfecting wipes, which are widely used in hospitals and healthcare facilities, must be disposed of according to biohazard protocols if they are contaminated with infectious materials.[54] Even handwashing and feminine wipes, which are frequently thought of as safe to dispose of in toilets, can cause blockages and should be disposed of in the trash instead of being flushed.[71] Interestingly, regardless of whether they are biodegradable or not, wipes are accumulating in the environment (see Fig. 3). Long-term contamination from disposing of

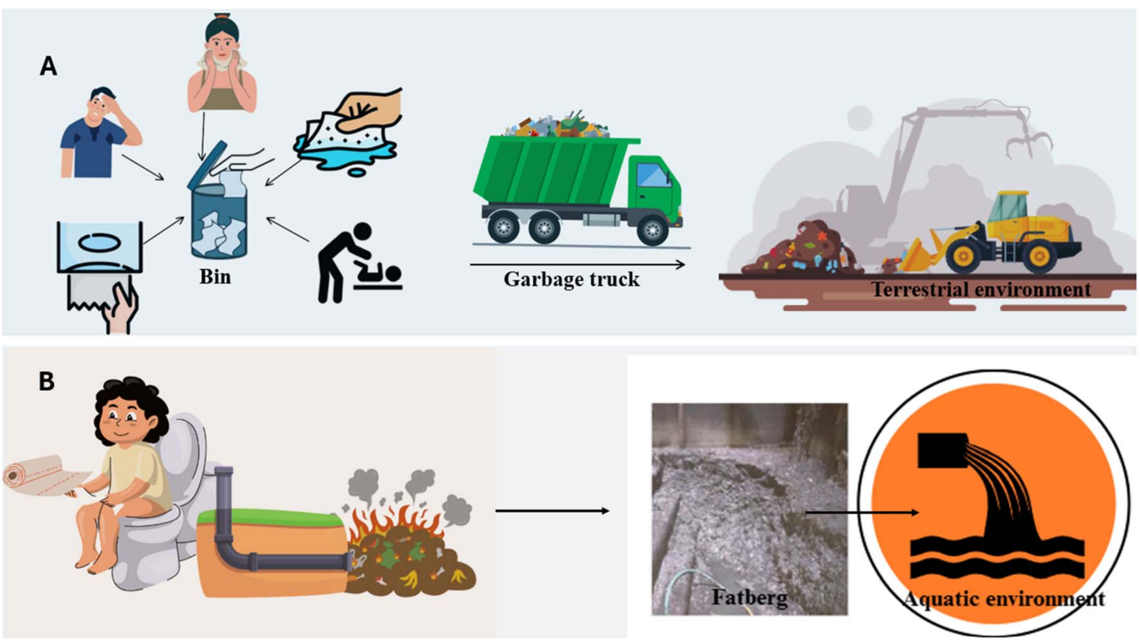

Fig. 3 Disposal route of wipes where wipes discarded in garbage or trash bin end up in landfill/soil (A) (created with Canva), while flushed wipes reside in the aquatic environment through municipal wastewater (B) leaving fatberg.[12]

non-biodegradable wipes can be reduced by adopting more environmentally friendly substitutes, implementing conscientious waste management practices, and strengthening laws.

3. Reasons for concern

3.1 Flushability

Flushability refers to the ability of a product to pass through household plumbing and municipal wastewater systems without causing blockages or operational disruptions. Industry organizations define flushability differently. According to INDA, a flushable wipe should clear toilets, move freely through drainage pipes, and break down in wastewater treatment without causing obstructions. On the other hand, the International Water Services Flushability Group (IWSFG) sets stricter criteria, requiring that flushable wipes disintegrate rapidly, contain only easily degradable materials, and exclude plastics or regenerated cellulose (Lundeen, 2017).

Certain types of wipes, such as moist toilet tissue, are specifically designed to be flushed. In contrast, others, including baby wipes, personal care wipes, and disinfecting wipes may not be designed to be flushed down. Due to such ambiguity or unawareness most of the time, people discard wipes where it is not suitable to be discarded.[70] Unless it is flushable, wipes need to be discarded into a garbage bin instead of being disposed of in the sink or toilet. However, the disposal instructions on the wipes are even more misleading. As a result, issues such as clogging of sewage lines and accumulation of plastics are becoming quite common.[72] Interestingly, while manufacturers may label products as flushable, real-world wastewater studies reveal a different story. Studies have shown that some wipes marketed as "flushable" fail to disintegrate properly in sewage systems, leading to costly blockages and environmental contamination.[73] Moreover, 50% of wipes labeled as flushable contain polyethylene terephthalate (PET), making them non-degradable and a source of microplastic fibers in the marine environment.[22]

A study testing 23 wipes marketed as flushable found that none fully disintegrated under standard sewer conditions, and many persisted in pipes and wastewater treatment facilities, contributing to blockages.[66] These improperly flushed wipes accumulate in municipal sewer systems, forming large masses known as fatbergs, which clog pipes, damage infrastructure, and increase maintenance costs for cities and consumers alike.[1,66]

So, why do some wipes fail to flush properly? The answer lies in their fiber composition and structure. Many wet wipes are made with long, strong fibers that resist breaking apart in water. The presence of synthetic binders and non-water-soluble adhesives further reinforces their structure, preventing them from dispersing like toilet paper. Even in cases where wipes initially meet flushability standards, their dispersibility can degrade over time, particularly for wet-laid hydroentangled wipes, which tend to lose their ability to break apart after prolonged wet storage.[66]

Ultimately, flushability and degradability are not the same.[18] A wipe that clears a toilet bowl does not necessarily break down within the sewer system. Without clear industry standards and consistent product labeling, confusion persists, leading to ongoing environmental and infrastructure challenges. Addressing these issues requires a closer examination of wipe formulation, testing protocols, and consumer awareness to ensure that only truly flushable products enter our wastewater systems.

3.2 Biodegradability

Degradability is defined as the ability of a material to break down into low-molecular-weight compounds, with end products such as carbon dioxide, water, and biomass.[74,75] Biodegradability of wipes specifically refers to the capacity of the broken structure into constituent fibers to disintegrate into fine particles that can be metabolized by naturally occurring microorganisms in soil, landfill, wastewater, and other environmental settings.[76,77] This definition is critical because it establishes that a wipe must not only physically disperse but also undergo complete microbial degradation post-disintegration.[66,78]

Pantoja Munoz *et al.* (2018) conducted an in-depth experimental study to characterize the material composition of commercial wet wipes. They found that they typically contain not only biodegradable cellulosic fibers derived from wood pulp, viscose, or similar sources but also synthetic polymers such as polyester (polyethylene terephthalate, PET), high-density polyethylene (HDPE), and polyethylene/vinyl acetate (PEVA/EVA).[20] This heterogeneous blend raises significant concerns because the presence of synthetic components, even if the product physically disintegrates, may impede complete biodegradation and lead to the persistent release of microplastics into aquatic environments.[79] Many existing commercial wipes in the market contain 100% polyethylene, polypropylene, or other thermoplastic bicomponent because of their low-cost, high production rate manufacturing process, such as spunbond and meltblown.[28,36] Such fibers do not degrade and tend to accumulate. For example, polypropylene lost only 5% of its weight after 90 days of soil burial test, while polyester terephthalate (PET) lost only 20% after composting at elevated temperatures.[21] Table 3 illustrates the persistent nature of some synthetic polymers commonly used in wipes. The advantages of natural polymers in wipes are often offset by the blending of synthetic polymers that accumulate over time.

Wipe materials can degrade through a variety of mechanisms, including physical disintegration, chemical hydrolysis, photodegradation, thermal degradation, and microbial enzymatic degradation[95] as depicted in Fig. 4. Chemical hydrolysis and photodegradation involve the cleavage of polymer bonds under the influence of water, heat, and UV light,[96,97] whereas microbial degradation is mediated by extracellular enzymes secreted by bacteria and fungi that break down cellulosic fibers.[77,80] The biodegradability of a material is influenced by several factors such as chemical composition, crystallinity, degree of polymerization, molar mass, hydrophobicity, finishing agents, as well as time, pH, and other environmental conditions.[98,99] Fig. 5 illustrates that, unlike synthetic fibers, naturally derived fibers are hydrophilic and attract moisture, thereby facilitating degradation within several weeks which was visible by soil burial test.

Table 3 Biodegradation of some naturally derived and petroleum-based polymers in different environments

Polymer	Settings	Degradation status	Ref.
Cellulose	Aerobic (soil)	89.4% Weight loss occurs after 120 days	80
	Aerobic (marine)	80% Biodegradation occurs within 30 days	81
	Anaerobic (landfill)	Approximately 95% of the weight loss occurs within 45–49 days	82
	Compost	Approximately 90% CO_2 evolves within 30 days of compost conditioning at 55 °C	83
Viscose	Aerobic (soil)	98.1% Weight loss occurs after 120 days	80
		Total organic compound reduced to approximately 350 (mg L^{-1} $\times 10^3$)	
Cellulose acetate	Aerobic (fresh and seawater)	>90% Biodegradation occurs within 100 days and 30 days, respectively, in fresh and seawater	84 and 85
	Anerobic (sewage sludge)	80% CO_2 evolves after 29 days	86
Linen	Anerobic (sludge)	7.20–12.90 liter biogas produced from anerobic settings for 40 days compared to PET, which produced 0.4–1.4 liter	87
Tancel	Aerobic (soil)	59.3% Weight loss occurs after 120 days, and the total organic compound produced is approximately 500 mg L^{-1} $\times 10^3$	80
Hemp	Aerobic (soil)	66.17% Weight loss occurs in just 11 days	88
Jute	Aerobic (soil)	24.01% Weight loss occurs in just 11 days	
PLA	Anaerobic (landfill)	20% Weight loss in 45–49 days	82
	Compost	Approx. 70% CO_2 evolves after 30 days at 55 °C	83
PHBV	Compost	40% Mineralized in 78 days at 40 °C	89
PHB	Compost	80% CO_2 is produced after 28 days at 55 °C	83
PHBO	Anerobic (simulated landfill)	41.1–52.5% Mineralized to methane and carbon dioxide in 40 days	90
PP	Anerobic (compost)	4% CO_2 evolved after 80 days	91
		Yield an extremely high of 94% total organic compound after 45 days	
	Aerobic (controlled laboratory environment)	No CO_2 evolves after 45 days, and high 94% total organic compound contents are recorded	92
	(marine environment)	Only 0.7% means biodegradation	93
PET	Aerobic (soil)	Only 12% CO_2 evolved after 100 days in natural soil	21
		Only 1.4% weight loss was calculated after 120 days of soil burial	
	Aerobic (marine)	Overall biodegradation is 2.5% with a 0.5 g CO_2 evolution after 90 days	80
	Aerobic (marine)	80% CO_2 evolved in the compost condition at 65 °C	93
PE	Aerobic (soil)	No weight loss was recorded after 1095 days of the soil burial test	94
	Compost	At 58 °C, approximately 18% CO_2 evolves from PE	
Polyamide	Aerobic (marine)	0.3% of total biodegradation was reported after 90 days	93

Wiping chemicals impregnated in wipes can also slower the biodegradation rate. Although less studies are found to confirm the effect of such wiping ingredients on microbes, some of the disinfecting and preservative chemicals, especially when used in industrial and household wipes are identified as hazardous to certain microorganisms. A recent review noted that quaternary ammonium compounds (QACs) cause acute and chronic toxicity to sensitive aquatic organisms, with environmental concentrations of some QACs approaching levels of concern for ecosystems.[101] Disinfectants like phenol-based compounds can bioaccumulate in aquatic organisms and disrupt their endocrine systems. Preservatives like parabens can pose hormonal disruption.[102] Using such additives ultimately restrict microbes to accumulate on the wipes surface. Enhanced durability, abrasion resistance, and softness due to the chemical treatments or additives[65] offset the surface disintegration of wipes. Additionally, coating of hydrophobic finishes or lotions sometimes adhere to the surface in a way that it persists a prolonged period of time leading to poor degradation in environmental conditions.[103]

The importance of biodegradability in flushable wipes lies in its potential to prevent long-term environmental pollution and reduce the accumulation of persistent microplastics in sewer systems and aquatic environments.[20,74] Environmentally friendly wipes minimize the risk of sewer blockages and decrease the burden on wastewater treatment facilities.[18,104] Moreover, by using biodegradable materials, manufacturers can align their products with circular economy principles and lower the overall ecological footprint associated with disposable hygiene products.[80,105]

3.3 Microplastic pollution

Microfibers have emerged as a significant environmental concern due to their presence in nonwoven products such as wipes, which often originate from synthetic materials and measure less than 5 mm in diameter.[106] The release of microfibers from wipes depends on both composition and usage conditions.[23] Li *et al.* (2022) discovered that the microfiber emission from wipes occurs when users apply friction to the material, resulting in 10^6 to 10^8 fibers per sheet with lengths of 752 μm that match the size of polyester fibers.[107] Studies indicate that wet wipes contribute substantial amounts of microfibers when exposed to water—research[108] highlights that polyester fibers are among the predominant materials released.

Most microfibers detected in aquatic systems originate from synthetic textiles across several types. Scientific studies demonstrate that microfibers exhibit considerable variability in their dimensions, ranging from longer lengths that measure up to 5000 μm.[109] The shedding behavior of microfibers exhibits different patterns due to the influence of fabric types, washing

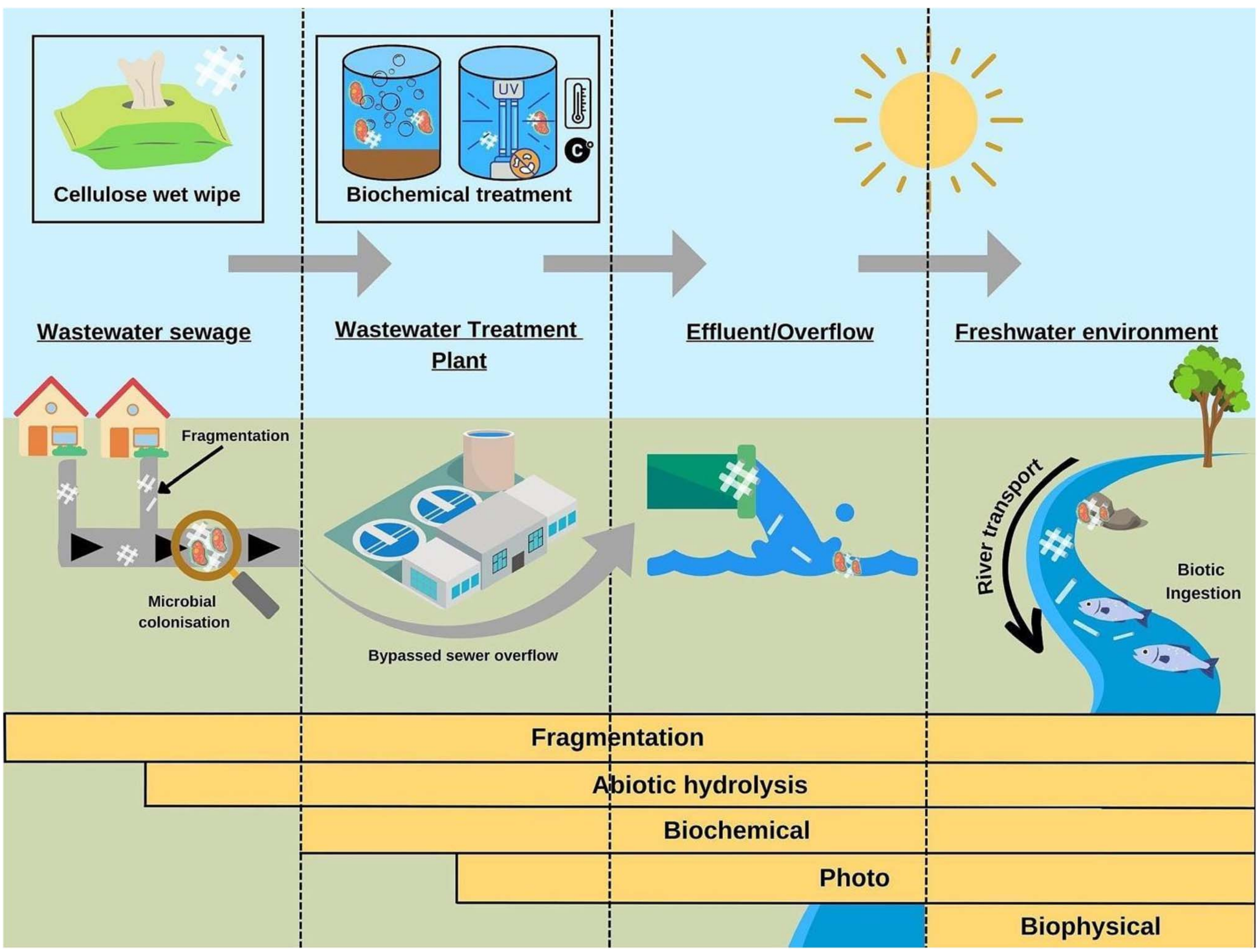

Fig. 4 Degradation stages of flushed cellulose wet wipes. Reproduced with permission from ref. 18. Copyright 2023, Elsevier B.V.

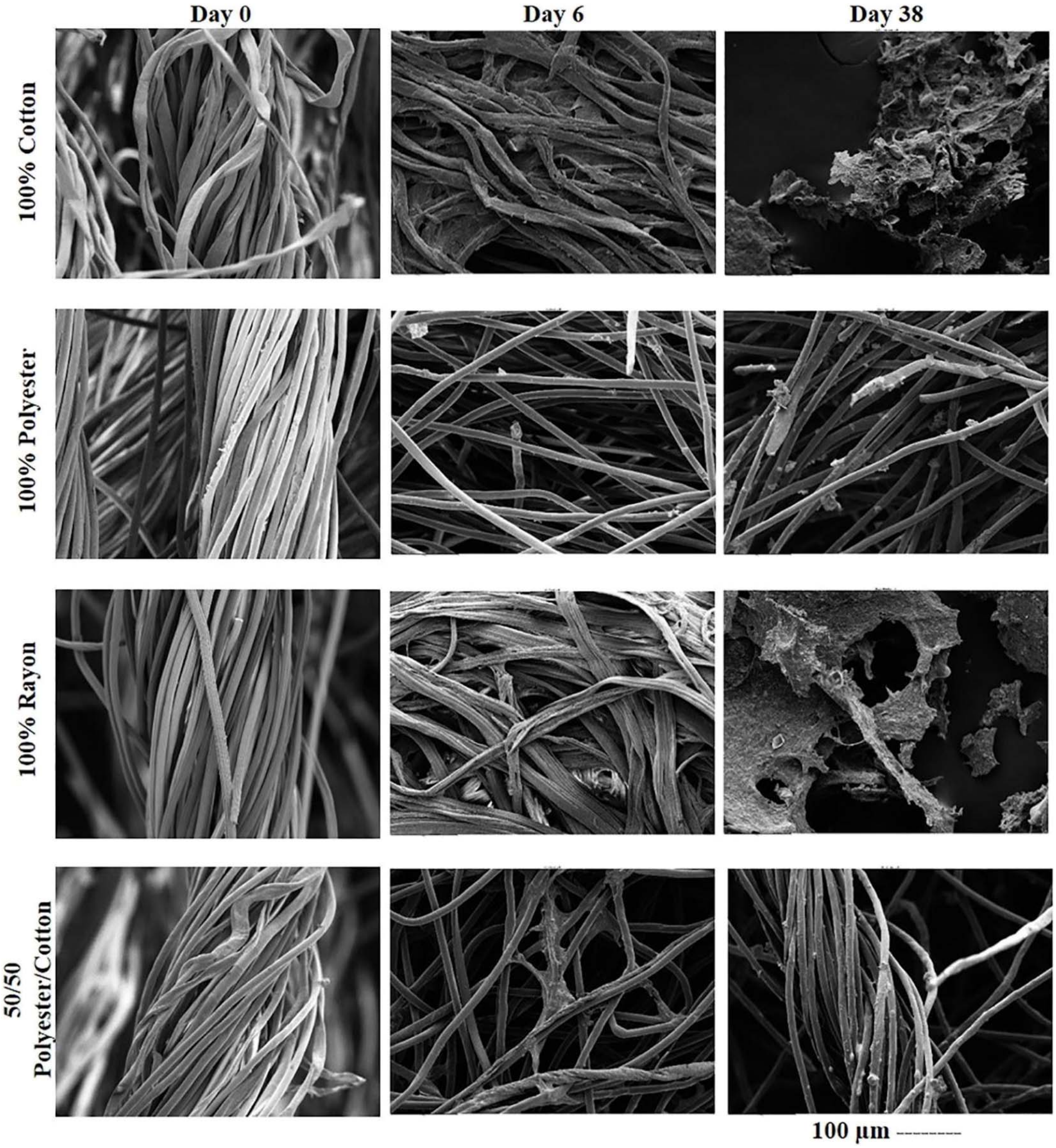

Fig. 5 Comparative scanning electron microscopic view of the degradation of 100% cotton, 100% polyester, 100% rayon, and 50/50 polyester/cotton fiber. After 38 days of soil burial test, weight loss of 100% cotton, 100% rayon is evident, while polyester and its blend remain almost unchanged. Reproduced with permission from ref. 100. Copyright 2019, Elsevier Ltd.

mechanisms, and user-related mechanical interactions on the shedding process.[109] A single wipe sheet can release 693–1066 particles when exposed to an aquatic environment and 106–180 particles during a simulated washing process, where a considerable number of polyester microfibers are shed in wet conditions when flushed down a toilet.[110] Fibers from heavier fabrics tend to shed more microfibers than those from lighter fabrics, and short-stapled fibers are more likely to release microfibers.[111] Additionally, factors such as the moisture content of wipes and the friction generated during use influence microfiber shedding mechanisms.[107]

Web formation and bonding techniques also contribute to microfiber shedding. A study on microfiber release from different commercial wipes concluded that average microfiber release from personal care wipes and household wipes accounts for 26–27 mg g^{-1} of wipes, which is higher than that of industrial wipes.[28] Meltblown polypropylene with lower DCD sheds less microfiber due to strong bonding. Natural cellulose-based nonwovens produce higher yields, while the hydroentangling process reduces microfiber shedding. Nonwoven materials, including textiles with natural fibers, release additional microfibers due to their uneven structure and weakened fabric stability when immersed in water, according to ref. 28.

Microfibers function as pollutant and pathogen carriers, which pose health dangers when people ingest or inhale them.[112] Millions of microfibers can escape from laundry during just one washing cycle, thereby increasing ocean and river pollution levels.[113] Additionally Fig. 6 shows role of wet wipes to increase microplastic accumulation in the ocean bed significantly alarming.[22] The ingestion of microfibers results in both

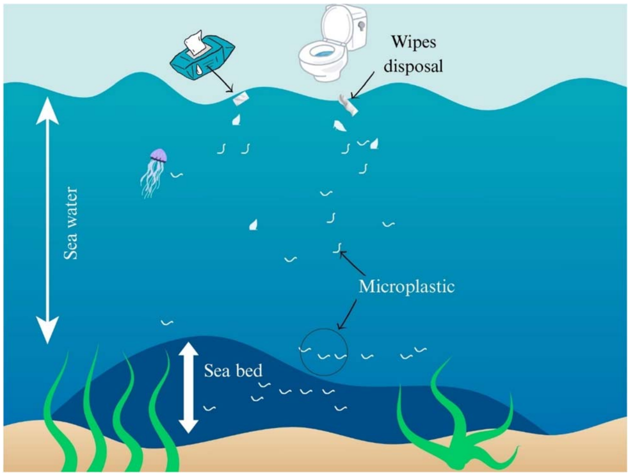

Fig. 6 Contribution of wet wipes to microplastic fiber pollution in the marine environment (created with Canva).

digestive tract blockages that cause harm and decrease the reproductive capability of aquatic species.[79] Microfibers accumulating within food chains raise significant concerns because the transfer of dangerous substances from lower to higher trophic levels could end up in the human food chain.[114] Microfiber degradation produces toxic substances that endanger the quality of water bodies while harming marine organisms.[115]

From the discussion above, several factors have been identified as responsible for the common issues associated with disposing of wipes (see Fig. 7). These factors span the compositional characteristics of the polymer used for wipes, including physical parameters, as well as processing steps. While degradability is simply dependent on the raw materials' chemical and physical properties, flushability is influenced by the structural engineering of the nonwoven, particularly how the fibers are bonded within the substrate. Meanwhile, microfiber release depends on several factors that might be linked to the former issues. Understanding the effects of these factors may help challenge these issues.

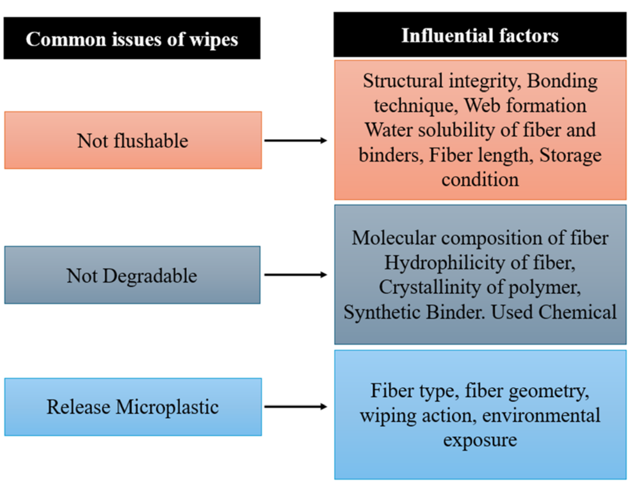

Fig. 7 A list of factors influencing flushability, degradability, and microplastic release of wipes.

4. Potential solutions

4.1 Selection of raw materials

The selection of materials is the first and most crucial step in developing wipes that cause minimal environmental issues. For wipes, the materials used include polymeric fibers and binders. In addition to polymer, chemicals are added to wipes for functional purposes, which is a negligible percentage compared to the overall weight. An ideal selection of degradable fibrous materials can enhance fiber properties, thereby improving degradability and dispersibility, which helps solve landfill and sewerage clogging issues.

Natural polymers enhance the biodegradability and flushability of disposable wipes while maintaining their performance integrity. Cellulose collected from wood and non-wood sources is mostly used in wipes. Cellulose from wood pulps is commonly used,[44] while cotton, flex,[116] bamboo, Kenaf, corn stock,[105] and pineapple leaves[117] are also deemed promising non-wood sources for wipes. Regenerated cellulose (RC), such as viscose,[118] lyocell, Danufil[30,53] and rayon, is also used extensively as virgin material or as a blended form with other RC or cellulosic or degradable synthetic polymers.[119]

The biodegradation of cellulosic fibers used in flushable wipes proceeds rapidly, with microbial enzymes efficiently hydrolyzing polymers into low-molecular-weight compounds[77,80] (Park *et al.*, 2004; Sülar & Devrim, 2019). Furthermore, natural fibers such as cotton, viscose, and lyocell are inherently more susceptible to aerobic microbial attack due to their hydrophilicity and the abundance of amorphous regions in their structure, which facilitates enzyme penetration and chain scission.[64,66,75] During this process, microbes first attack the material, starting to deteriorate the surface, depolymerize into oligomers and monomers, and then convert organic carbon into inorganic products in the mineralization stage (see Fig. 8). The surface of wipes is often deteriorated or broken down by abiotic and biotic media, however, not fully mineralized, leaving microplastic.[100] The presence of petroleum-based substances (fibers or binders) is the prime reason for such prevalent microplastics.

Microplastic release and degradability are linked and primarily influenced by the raw materials used. The use of fully degradable natural fibers not only addresses the degradation issue but also reduces microplastic generation. Although shorter length cellulosic fibers were found to release more microfibers,[120] in the aquatic environment, they are also quickly mineralized by microorganisms[18] and hence should not persist in the environment.[121] Fig. 9 shows that cellulose-based fibers have also exhibited rapid biodegradation in all aquatic environments compared to synthetic polyester and its blends. However, wetting chemicals used in wipes, such as antibacterial liquids, disinfectant agents, might restrict the initial colonization of microbes on the substrate, delaying the biodeterioration stage.[121,122] In this case, structural engineering of wipes, such as

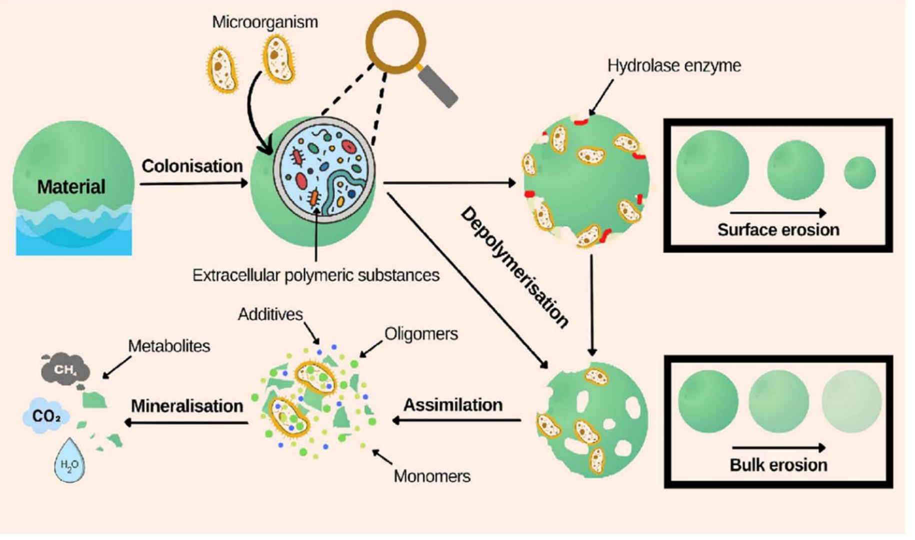

Fig. 8 A step-by-step process of biodegradation, led by an organism, starts with colonization on the material, followed by depolymerization, assimilation, and mineralization processes. Reproduced with permission from ref. 18. Copyright 2023, Elsevier B.V.

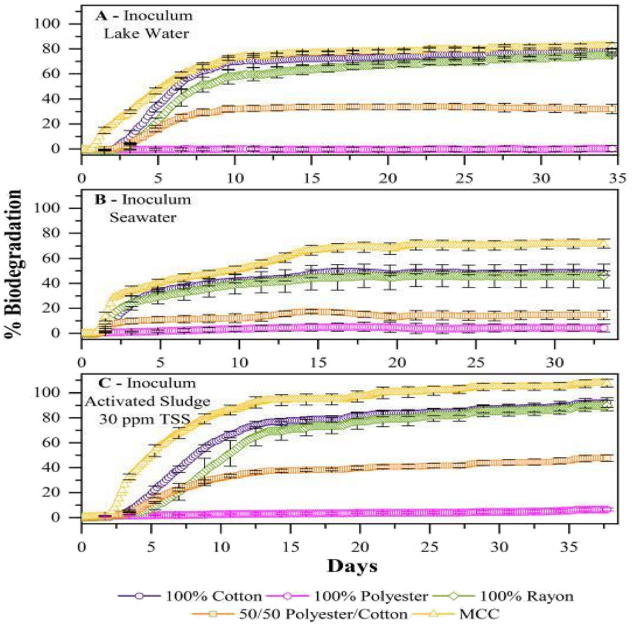

Fig. 9 Comparative biodegradation among cellulose-based fibers and fully synthetic or their blends in several aquatic environments such as (A) lake water, (B) sea water, and (C) activated sludge. Reproduced with permission from ref. 100. Copyright 2019, Elsevier Ltd.

increasing surface area and smaller pore size by lowering fiber diameter, can be introduced to attract more microbes.[123]

Combining different cellulosic fibers can further improve performance, degradability, and dispersibility. For example, Bhatiyari (2023) 85% viscose with 15% cotton to manufacture soft skincare wipes. Higher content of viscose provided excellent softness due to its greater moisture content. Long, viscose fibers and wood pulp have been shown to provide sufficient strength during use while retaining their dispersive properties.[53] A blend of 20% lyocell and 80% wood pulp can disintegrate by over 90% in just 30 minutes[124] and enhance biodegradability. Biodegradability can also be enhanced by incorporating bast fibers, such as hemp and flax. Highly water absorbent flax improves wet tensile strength and biodegradability by increasing water absorption when added to viscose at a 30/70 (flax/viscose) ratio.[116] Table 3 presents several patents that utilize biobased polymers in the production of sustainable wipes.

Molecular composition and structure of cellulosic and regenerated cellulose enable microorganisms in the environment to break them down and degrade faster compared to synthetic polymers.[27] Indeed, wipes made from 100% cellulosic materials, or their blends, are biodegradable.[116] However, the rate of degradation varies due to microstructural variations. For example, 50 GSM spunlace cotton wipes have a 12.6-day half-life degradation, whereas a wipe made of rayon of equal basis weight have 7.6 days.[125] The comparatively faster degradation of regenerated rayon wipes is attributed to its lower crystallinity. Higher crystallinity of cellulosic wipes slows their degradability in abiotic environments; however, in wastewater, sewage, or aquatic environments, hydrolytic degradation occurs faster.[18] Cellulose acetate is highly degradable in both aquatic and marine environments. High-strength, finer-diameter cellulose acetate fibers produced through wet spinning[126] can be utilized for the production of heavy-duty nonwoven wipes.

Regenerated cellulose fibers, including viscose and lyocell, are biodegradable and offer better performance than synthetic fibers in the environment. However, these fibers may need more force to break down in sewer systems compared to unmodified cellulose. The advantage of using bast fibers is not having crimps or kinks on the bast fiber, which might help with easy disentanglement.[127]

To avoid disruption of microbial activities, careful selection of wiping chemicals is also needed. The biodegradable and less harmful properties of plant-derived antimicrobials, such as thymol from thyme oil and biopolymers like chitosan, have demonstrated effective antibacterial properties.[67] In addition, sodium benzoate and potassium sorbate are safer alternatives to parabens and isothiazolinones, which are less ecotoxic and less likely to disrupt endocrine function.[102] Because of their low toxicity and rapid biodegradation, organic acid-based disinfectants such as citric acid, lactic acid, and levulinic[128] acid are gaining popularity as safer alternative.

4.2 Dispersibility

Dispersibility is the first step in biodegradation and is also an essential characteristic for addressing the issue of sewage clogging caused by flushable wipes. Dispersibility of flushable wipes is a measure of how effectively they break down into smaller components when exposed to water. Although material types govern degradability, dispersibility partly depends on the physical parameters of the fiber, such as fiber length, L/D ratio, and bonding technique.[26,56] Dispersion is interrupted when the length of the constituent fiber is more than 20 mm.[129] Studies claimed that short fibers improve physical dispersibility, whereas longer fibers need force to break down. Wipes made from unbleached softwood kraft pulp maintain good dispersibility even after longer wet storage, making them less likely to contribute to sewer blockages.[66] The length of pulp usually falls below 5 mm, which is the prime cause of dispersibility.[82]

Disentanglement of fibers in wipes also depends on the aspect ratio (L/D) and flexural rigidity.[26] Usually, fibers have a length thousands of times longer than their diameter. When the diameter of a fiber increases, the L/D ratio decreases, and flexural rigidity increases. If the aspect ratio exceeds a critical value, the fiber behaves flexibly, allowing it to bend, twist, and entangle with the surrounding fiber.[130] Therefore, the decrease in L/D ratio enhances dispersibility. Fig. 10 illustrates how short fibers bend and entangle together compared to the longer fibers, facilitating dispersibility. The use of shorter fiber lengths, such as pulp, that rapidly disentangle when exposed to water at minimum pressure, enhances flushability; however, this easy dispersion has also disadvantaged wet strength.

There are some other causes that affect the dispersibility of wipes such as aging time, wetting liquid being used and mechanical action[66] investigated the effect of storage time and condition on the dispersibility of wet wipes, as it takes at least 168 hours from wipe manufacturing to sale. Viscose/pulp blended wipes were produced using the wet-laid process and stored in two types of liquids: water and lotion, to meet the end-user requirements. The slosh box disintegration test revealed that both storage conditions reduce dispersibility to 80–90% within just 150–250 hours. Deterioration of dispersible rate in water is higher than that of lotion at a given time due to long-term swelling of the cellulosic fiber, which reduces interdiffusion between fiber interphases.[64] These mechanisms can increase adhesion between fibers over time, potentially reducing the dispersibility of fibers. Careful engineering of bonding mechanisms can play a crucial role in optimizing strength and dispersibility.

4.3 Choice of binders and bonding process

Most of the wipes made from renewable fibers are bonded either thermally, chemically, or mechanically, depending on their performance and aesthetic. Some wipes, such as industrial cleaning wipes, makeup removal wipes, and baby wipes, require good structural integrity and wet strength to perform their intended functions. For example, thermal-bonded wipes are durable and strong, comparable to hydroentangled or needle-punched wipes.[131] The difference in strength, types of binder affect dispersion and biodegradation. Several techniques can be used to enhance dispersibility in the case of thermal bonding while maintaining their strength. For this purpose, low

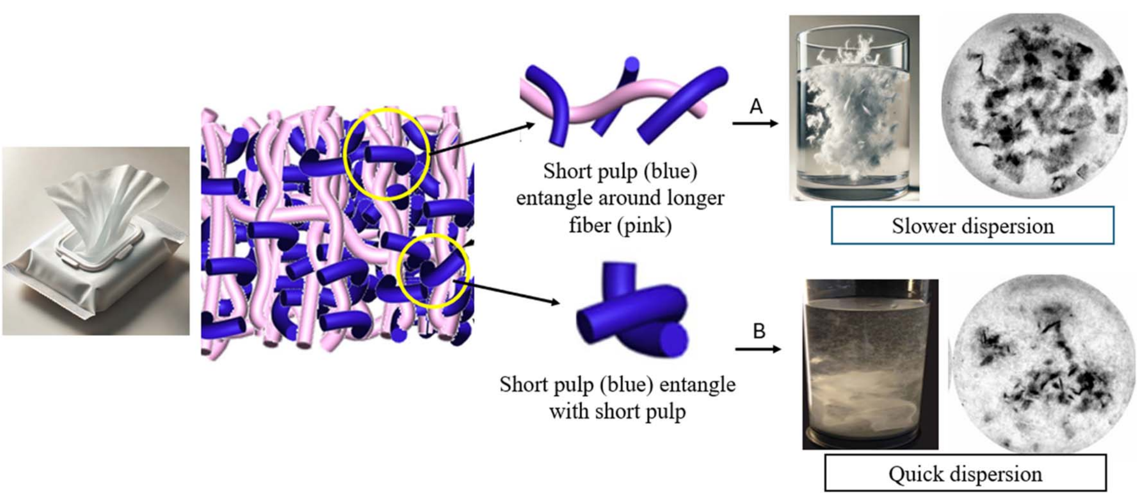

Fig. 10 Effect of short fiber length on the dispersibility of wipes in macro and microscopic view; slower dispersion occurs when longer fibers are strongly entangled (A). Published under the CC-BY License[53] Copyright 2018, The Author(s), Published by SAGE, and faster dispersion happens due to the minimum entanglement by the short fibers (B). Reproduced with permission from ref. 26. Copyright 2018, Springer-Verlag GmbH Germany.

molecular weight water-soluble polymers such as polyvinyl alcohol (PVA), acrylic-based resins, and carboxymethyl cellulose (CMC) can be used.[132–135] Combination of PVA and CMC at a concentration ratio of 10%/0.4% provides the best dispersibility since both contain water-soluble functional groups.[136] Depending on the formulation and the environment, these binders can have varying solubility rates. For example, an acrylic binder can be made more soluble by adding unsaturated acid monomers and alkaline materials.[132] The solubility of CMC is related to its degree of solubility (DS) value, with higher DS values leading to faster dissolution.[137]

A myriad of biobased polymers can be utilized as biodegradable binders[25] talked about the potential of lignin, chitosan, cellulose acetate, cotton seed, alginate, soy protein, CMC, soybean oil, linseed oil as promising alternatives to synthetic adhesives and binders—a combination of such biobased alternatives balances between strength and degradability. A mixture of carboxymethyl cellulose, citric acid, CMC, and sunflower oil enhances the wet strength of nonwoven fabric used for outdoor applications.[138]

Using foam application and pad-curing techniques, soy protein isolate (SPI) as a bio-based binder was applied in viscose nonwovens.[139] In comparison to commercial acrylic binders, soy protein-based binders offer similar adhesion properties with higher biodegradability and environmental benefits.[139] In soil and marine environments, bio-based polyesters, such as polyhydroxyalkanoates (PHAs), are highly biodegradable. In addition, it demonstrates good wet strength and water tensile properties comparable to polypropylene binders.[140]

The best approach for bonding webs made of renewable polymers, which balances strength and degradability, is to adopt mechanical bonding, particularly the hydroentangling process. This process does not involve any chemicals and offers softness, making them ideal for hygiene applications. Water jet velocity, flow rate, and pressure can be adjusted to get the desired entanglement and strength.[141] Pulp or other short fibers are exposed to the wet laid process for web formation, which offers inferior tensile strength.[30] Wipes made from natural fibers are mechanically bonded[142] using the hydroentangling process to form wood pulp/Tancel (1 : 4) wipes. The water jet in

Table 4 A list of patents showing promising materials with a manufacturing process ideal for developing sustainable wipes

Patent number/ref.	Material	Web formation	Bonding	Fiber size	Novelty
US2021386251-A1 (ref. 143)	Viscose, lyocell, and cotton fibers	Hydroentangling	Non-adhesive or adhesive binder	Not specified	Reinforced base sheet with binding agent and wetting lotion, achieving tensile strength of 100–250 g-force per inch and water dispersibility
EP3550062-A1 (ref. 144)	Pulp (35%) and lyocell fibers	Hydroentangling	Excludes synthetic binders	Not specified	Produces biodegradable nonwoven web with high mechanical strength, using environmentally friendly materials and processes
WO2017003426-A1 (ref. 145)	Regenerated cellulose (up to 20%), natural cellulose (≥80%)	Hydroentangling	Not specified	Fibrillated cellulose	High tensile strength moist wipes (200–600 g-force), balancing wet machine- and cross-direction strength
US2016201268-A1; US9453304-B2 (ref. 146)	Natural cellulose, regenerated cellulose, and optional synthetic fibers	Hydroentangling	Ion-triggerable cationic polymer binder	Not specified	High wet strength (≥300 g-f per inch) and effective water dispersibility (≤180 g-f per inch), with improved stretchability
US2014/0259484-A1 (ref. 127)	Individualized bast fibers (flax, hemp)	Hydroentanglement	No binders	Mean length > 4 mm	Innovative use of straight, pectin-free bast fibers, reducing environmental impact
WO2013/015735-A1 (ref. 147)	70% pulp, 5% PLA fibers	Hydraulic entanglement	No binders or wet-strength agents	PLA: 8–20 mm, 0.5–3 dtex	Biodegradable material without added binders; balance of wet strength and flushability
WO2011/046478-A1 (ref. 148)	70% pulp, 30% manmade/natural fibers	Drylaid or wetlaid, hydroentanglement	No binders	Manmade/natural: ≥6 mm	Improved machine-direction wet strength due to fiber length ratio
WO2013/067557-A1 (ref. 149)	75–85% pulp, 15–25% Tencel	Wet lay process	Acrylic resin, epichlorohydrin	Tencel: 1.6–1.7 dtex	Fibrillated solvent-spun cellulosic fibers with rapid dispersibility and balanced wet/dry strength

the hydroentangling process, directed in the machine direction, enhances the tensile strength of the wipes. In addition, the dispersibility of wet-laid hydroentangled nonwovens is much higher than that of carded hydroentangled nonwovens.

Table 4 lists several patents that were utilized to develop more sustainable wipes, specifically in terms of biodegradability and flushability. The major function of wipes is to absorb liquid or liquid-like substances. The reason for using cellulosic fiber is its absorption properties and biodegradability. Most of the patents used pulp and natural fibers in the highest amount (70–90%), combined with another regenerated or biodegradable synthetic filament. The length of the fibers plays a crucial role in making the wipes dispersible. The smaller the fiber size, the better the dispersibility. The hydroentangling or spun lacing technique is a key aspect of all these patents, allowing for the effective bonding of fibers without the need for chemical bonding agents.

5. Challenges and scope of future work

In this article, we propose the development of sustainable wipes that comprise degradable materials, aiming to minimize landfill and dispersal issues. During this journey, several economic and technical challenges must be addressed. Economic challenges are closely tied to production speed, cost, and the processing of renewable raw materials, where technical challenges will highlight the need to optimize and balance essential parameters. This section will briefly describe these challenges and propose future work to address them.

High cost and slower production efficiency of renewable materials are disadvantages for promoting sustainable wipes, especially when having a longer length for wipes manufacturing. The web formation of natural fibers primarily employs the carding and wet-laid process. Wet lay is used to process short fibers,[150] especially wood pulp. Most of the other natural fibers are processed through the carding process. Still, both web formation processes have comparatively lower production rates than spunlaid processes used to make webs from thermoplastic, petroleum-based polymers. In addition, the processing, labor, and machinery costs for carding are also higher than those of the spunlaid process, which is detrimental to the affordability of sustainable wipes. Developing a high-speed carding process that modifies natural fibers into thermoplastic can mitigate such challenges. Recent research on thermoplastic starch (TPS) has shown that improves the biodegradability of composite materials.[151] Melt-spun TPS fiber would be an excellent option for sustainable wipes due to its production capacity and properties. TPS is expected to act as a biodegradable domain that initiates surface erosion and facilitates disintegration under composting or soil conditions.[151]

Biobased polyester and nylon can also promote degradable wipes. For example, biobased aliphatic polyesters like polyhydroxyalkanoates (PHA), polyhydroxybutyrate (PHB), and poly (3-hydroxybutyrate-*co*-3-hydroxyvalerate) (PHBV) are increasingly used to produce melt-spun fibers for nonwoven textiles. They are biodegradable, biocompatible, and have tunable mechanical properties. Utilizing these materials in nonwoven wipes will yield higher production efficiency without compromising degradability.[152,153]

Rapid swelling and interdiffusion of cellulosic fibers due to the hydrophilic property increase fiber–fiber and molecular interaction.[154] Long-term swelling along with interdiffusion might cause dispersibility aging, which can be mitigated by ionic shielding.[66] Ionic shielding occurs when cations such as Ca^{2+}, Mg^{2+}, and K^{+} leach from pulp fibers and neutralize negative charges on fiber surfaces. As a result, the fibrils are repelled from each other. This unique mechanism can be adopted to solve dispersibility issues caused by longer fibers.[64] Since the shielding effect neutralizes the negative charge of hydroxyl (–OH) groups on cellulose fibers, it could potentially reduce moisture uptake and impact biodegradation, which requires further research to confirm.

Another challenge with natural fibers is achieving optimum wet strength to perform wiping actions. The enormous hydrogen bonding between cellulose molecules of short pulp weakens the wet strength of wipe papers.[137] Although Regenerated cellulose improves wet strength,[76] longer lengths may impact the ability to disentangle easily. The blending of bast fibers and regenerated cellulose has the potential to optimize both parameters, which have not been explored yet. Modified water-soluble *N*-vinyl pyrrolidone-glycidyl methacrylate (NVP-GMA) binder chemically improved wet strength and breaks down completely within 30 s in flushed water.[137] Further research is needed to investigate the effect of varying cellulosic fiber lengths, both with and without blending, on wet strength.

Agricultural waste can be leveraged to produce biodegradable nonwoven wipes using carding and needle punching, or any other suitable method. Tons of waste from secondary and primary crops, such as wheat straw, rice husk, corn husk, sugarcane bagasse, banana fiber, pineapple leaves, cotton linters, *etc.*, are discarded and burned.[155] Many studies (see Table 5) have already demonstrated the successful development of fibers or nonwoven sheets from discarded agricultural wastes.[117,156–158] Although nonwovens made from such fibers are mostly intended for applications such as acoustic, thermal, and filtration, they utilize materials from waste.[111,159] Very few studies have explored their potential in hygiene applications, such as wipes. Bast fibers from banana, hemp, kenaf, *etc.*, can also be softened[160] and cut into small lengths prior to carding and bonding to make nonwoven for industrial wipes.

A series of test protocols needs to be developed to propose standard testing for evaluating sustainable wipes, where degradability and flushability can be assessed. A detailed material composition analysis is crucial, as it documents polymer types, additives, and manufacturing processes, which[41] influence biodegradation behavior.[75] Real-time sensors and standardizing methodologies across different environments, such as aquatic, terrestrial,[95] and materials, are essential for data consistency and reliability. Fig. 11 illustrates the viable process flowchart with compatible techniques of manufacturing sustainable wipes from renewable fiber sources

Table 5 Nonwoven wipes production, properties, and application process from agricultural waste

Fiber type from agricultural waste	Web formation/ bonding technique	Properties and applications	Ref.
Corn stalk pulp	Wet lay/chemical binding	• Dispersible under standardized testing conditions, good mechanical properties, and water absorption rate was more than 600%, excellent for flushable wipes • Excellent for flushable wipes	105
Kapok fiber/waste cotton	Carding/needle punch	• Diameter of Kapok fiber is 20.5 ± 2.4 μm • Excellent oil sorbent and oil spill clean-up	161
Okra stem waste	Cross-lapping/ needle punch	• Average fiber diameter 22–32 μm • Exhibits good mechanical strength	156
Coffee cherries/cotton waste	Carding/needle punch	• Porous structure • Mean porosity ranges from 70.11–82.21% • Excellent sound absorber	162
Cotton cards fly waste/comber noil	Carding/needle punch	• Tensile strength is higher than wool • Biodegradable, cost-effective, good for food packaging	163
Corn husk and banana stem waste	Wetlay/NA	• Pretreatment with baking soda and vinegar improves softness • Basis weight ranges from 400–600 gsm • Promising application as nonwoven sheet	157
Extracted cellulose from *Hibiscus sabdariffa* bast fiber	Carding/ hydroentangling	• Good overall moisture management capability non-implantable feminine hygiene textile product	164
Milkweed	Carding and airlay/ needle punch	Good oil absorbent capacity than polypropylene nonwoven, can absorb 37.9 g per g oil. Nonwoven wipes have a mean pore diameter of 20.52 μm and thickness of 5 mm	165

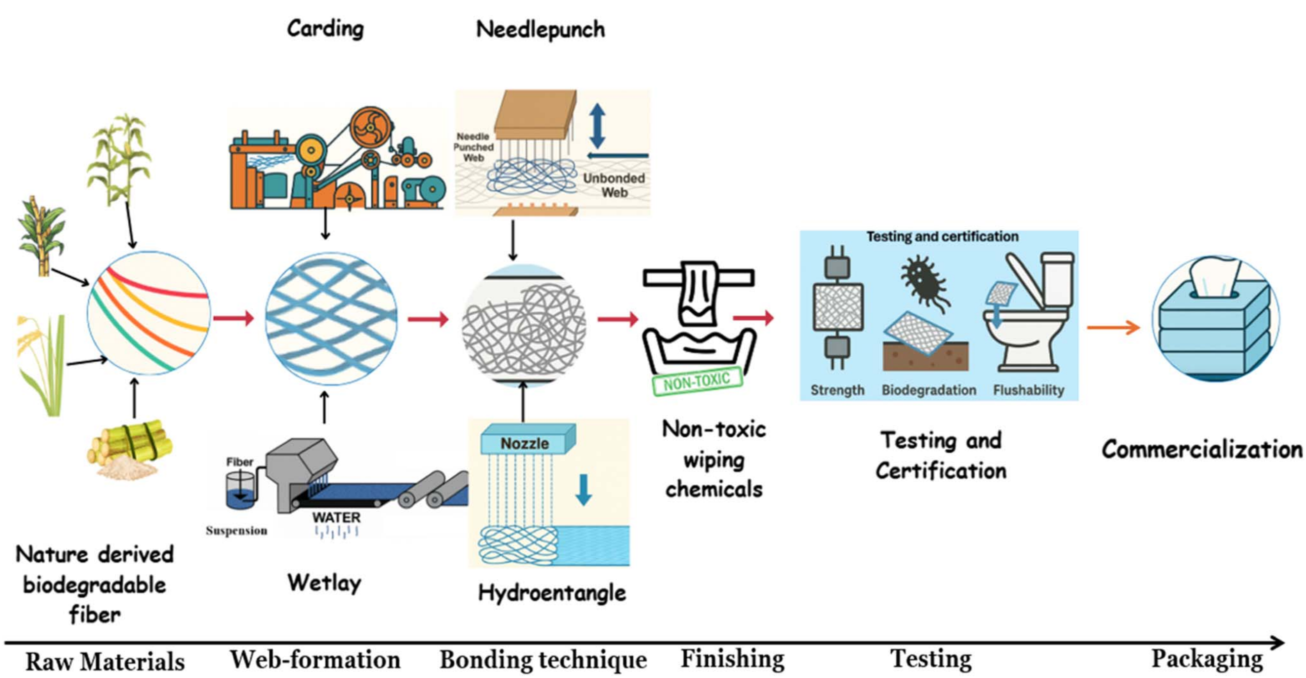

Fig. 11 A schematic step-by-step process diagram of developing sustainable wipes from nature-derived biodegradable fibers up to the packaging stage with compatible web formation, and bonding techniques, consideration of wiping chemicals, and required testing (created with Canva).

which are designed to minimize landfill and dispersibility issues.

6. Conclusions

Both industry and academia must give the mounting environmental and infrastructure issues associated with nonwoven wipes immediate attention. To mitigate such issues, the development of sustainable wipes is in demand. Sustainable wipes are nonwoven wipes manufactured in a way that allows them to degrade quickly in the environment and do not clog sewage lines. The material composition, web structure, and bonding methods are important determinants of disposable sustainable wipes. This review highlights the potential concerns associated with disposing of wipes in various environments and critically evaluates the causes of several related issues. In addition, the potential existing solutions, their pros and cons, and paths to overcome technical challenges are thoroughly discussed here. The main takeaways from the article are listed below:

(1) Disposable wipes contain synthetic fibers or blends of those, contributing to waste generation, sewage blockage, landfills, and microplastic pollution. Regardless of the disposal method, all the wipes end up in vicinity of nature, either in landfills or aquatic systems, which require rapid degradation.

(2) The biodegradability of wipes primarily depends on the properties of the raw materials, while flushability is related to the structural integrity or bonding mechanism of the nonwoven web. To become sustainable, wipes that are not flushable need to be biodegradable, while flushable wipes need to be both readily disintegrable and biodegradable.

(3) Careful selection of fiber from natural sources can help mitigate degradation issues and reduce microplastic release. Fibers derived from agricultural waste, recycling, or regeneration are viable alternatives for developing sustainable wipes. The selection of binder also plays a role in flushability and degradability. Binders, if used, need to be water-soluble and biodegradable.

(4) Optimizing between flushability and wet strength, which is necessary for wiping action, is challenging for nonwoven wipes made with natural fibers. Considering end use, desired characteristics can be achieved by engineering fiber geometry, utilizing blends, modifying surface, introducing special treatments, and bonding mechanisms.

(5) The spunlace process, a combination of carding and hydroentangling, is the most suitable process for manufacturing sustainable wipes. Biodegradable melt-spun synthetic fibers might be economically viable in terms of production efficiency and cost considerations. A holistic test method incorporating the required standards is needed to address the issues and certify sustainable wipes.

Addressing the technical and economic barriers through interdisciplinary research and standardized testing protocols will be vital in establishing a new generation of sustainable wipes. Only through such comprehensive approaches can the industry move toward products that meet both functional demands and environmental stewardship.

Author contributions

M. S. I. conceived the idea, developed the methodology, wrote the original draft, created visualizations, supervised the project, and performed proofreading; M. J. S. contributed to writing the original draft, worked on visualizations, edited the manuscript, curated data, and conducted formal analysis; A. V. F. contributed to writing and editing the manuscript and assisted with the literature review; J. O. contributed to writing the manuscript, performed investigation, and participated in the literature review; T. I. contributed to writing, editing, and proofreading the manuscript, worked on visualizations, supervised the project, curated data, validated results, and provided resources.

Conflicts of interest

The authors declare they have no conflicts of interest.

Data availability

All data findings are included within the manuscript.

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