Flushed But Not Forgotten: The Rising Costs and Opportunities of Disposable Wet Wipes

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The increasing popularity of single-use wet wipes across a variety of applications has caused environmental and economic challenges. Due to their convenience and low cost, disposable nonwoven wipes have become a necessity in the lives of many. However, consumers rarely consider the end-of-life of these items. Despite efforts from stakeholders, including wipes manufacturers and wastewater experts, there is frequent confusion among consumers regarding appropriate disposal. Many consumers flush wipes that are not compatible with municipal sewer systems, causing considerable damage. Additionally, wipes have poor environmental outcomes, as they often contain non-renewable plastics or are unable to biodegrade under disposal conditions. Previously, the wet wipes industry was projected to grow an average of 6% between 2021 and 2025; however, the use of these disposable items is projected to be much higher due to the COVID-19 pandemic. This paper reviews the market, key challenges, and technical properties of single-use nonwoven wipes. An emphasis is placed on the unique properties and associated challenges of flushable wipes. With strong market demands, consumers are unlikely to abandon single-use wipes, and therefore innovative solutions are required to solve the main environmental and technical challenges associated with flushable and non-flushable wipes.

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INTRODUCTION

The COVID-19 pandemic has led to an increase in the consumption of disposable, single-use disinfecting wipes as consumers are more concerned than ever about cleanliness and disinfection. However, few consumers consider what happens to the wipes after they are used. Most wipes are disposed of in household garbage and enter the landfill, where they take up to 100 years to decompose (Allen 2016). Despite guidelines surrounding "do not flush" labels, some consumers flush wipes down the toilet, leading to major blockages in sewage systems and wastewater treatment centres across the globe. Wipes that end up in landfills and waterways can leach microplastics into the natural environment (Karapanagioti and Kalavrouziotis 2019; Ó Briain *et al.* 2020).

The nature of this problem lies in understanding the composition of wipes. Most wet wipes are nonwoven textiles that are typically pre-soaked, shipped, and stored in a liquid or lotion formulated for its intended application. Wet wipes are used by many consumers as a safe and convenient way to clean their bodies and household surfaces.

There is increasing concern about the environmental impacts of these high strength cellulose- and plastic-based materials and their disposal. With a projected 1.36 million tons of wipes produced in 2020 and an annual growth rate of 6.3%, wet wipes are here to stay (Steed and Smithers PIRA 2018). The increasing environmental impacts of wipes represent a significant global challenge, and the massive scale requires multidisciplinary innovations to address critical questions. Additionally, improper disposal of these materials by consumers has serious economic consequences. How can eco-friendly materials be engineered to match the performance of, or possibly outperform, incumbent products while also remaining cost competitive? Beyond material properties, how can innovative product design challenge the status quo of wipes? What policy and regulatory changes are required to alleviate the negative impact of the environmental challenges associated with wipes?

This paper identifies the major environmental, economic, and social challenges surrounding single-use wet wipes, and it provides an assessment of the current wipes market. A study of the current products on the market was performed to better understand key industry players. Current industry guidelines and consumer education campaigns were outlined. Finally, an overview of the current technical status of wet wipes is presented, along with potential opportunities for future innovation and market disruption.

WHAT ARE WIPES MADE FROM?

Wipes are considered nonwovens, which are made up of individual fibres bonded together thermally, mechanically, or chemically. The constituent fibres of a nonwoven single-use wipe may be held together only by the entanglement of the fibres or, in the case of some flushable wipes, by using a chemical binding agent designed to fail in highly diluted aqueous environment when the wipe is flushed. The overall properties of a given wet wipe are determined by the characteristics of the fibres, binding agent, and the nature of the moistening liquid used.

Although most single-use wipes largely comprise cellulosic fibres, many non-flushable wipes contain non-renewable thermoplastic fibres, which are used because of their high strength and low cost (Munoz *et al.* 2018). Regenerated cellulose (RC) is often used as a significant component in most flushable and many non-flushable wipes. Regenerated cellulose is a class of fibre that is chemically identical to cellulose but is sometimes considered synthetic due to the fibres being modified (*e.g.*, dissolved and extruded) to improve properties such as strength. Although RC is biodegradable and made from a renewable feedstock, few studies regarding the biodegradation of RC in natural environments have been reported in scientific literature (Shibata *et al.* 2004). Wipes containing RC require more force to disintegrate in sewer systems, through dispersion in water, compared with those made of non-modified cellulose. Bioproducts, including those based on cellulose, are promising candidates for the development of nonwoven fibres and substrates with improved technical performance, degradability, and sustainability.

For bio-based materials to provide technical improvements, an understanding of the incumbent products must be reached. The following section summarizes the size of the global wipes market, the current products on the market, as well as market trends.

THE GLOBAL SINGLE-USE WIPES MARKET IS GROWING

Market Size and Breakdown

In a market study done by Smithers PIRA (2016, 2018), the global sales of wipes were projected to reach $19.6 billion USD by 2021 with a compound annual growth rate (CAGR) of 5.7%. However, manufacturers increased the production capacity of disinfecting wipes by up to 50% in 2020 due to consumer demand spiking up to 500% because of the COVID-19 pandemic (Olivo 2020). The long-term effects of the pandemic on the wet wipes industry are not yet known, but the market figures presented here are expected to be an underestimate because the increased demand resulting from the COVID-19 pandemic was not taken into consideration (Olivo 2020). It is expected that the large increase in consumer demand will stabilize within a few years of the end of the COVID-19 pandemic. Figure 1A shows the projected growth of the wipes industry through 2025. The CAGR estimate is based on reported past data, projected current data, and current projections of changes due to the COVID-19 pandemic (Zhang 2010a; Freedonia Group 2015; Smithers PIRA 2016; Smithers 2018; Data Bridge Market Research 2019; Fortune Business Insights 2020; Mordor Intelligence 2020; Research and Markets 2020; Technavio 2020; The Business Research Company 2020; 360 Research Reports 2020).

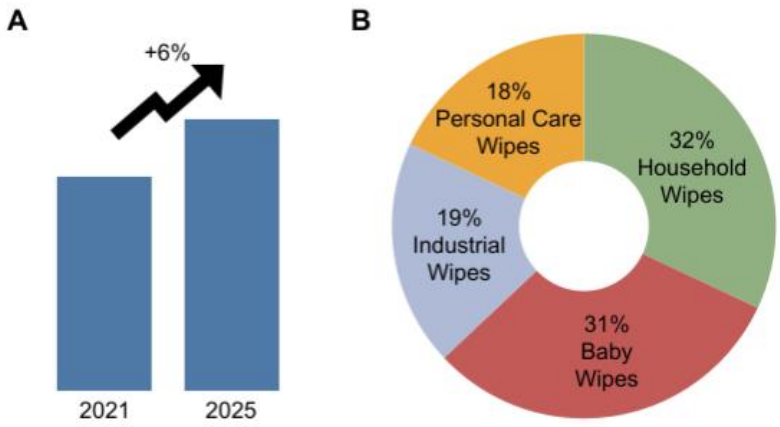

Fig. 1. (A) By comparing multiple market reports and articles, a compound annual growth rate (CAGR) of 6% was estimated for the next four years. (B) Market breakdown data are compounded from five market reports with data reported in value of global market share in USD (Zhang 2010a; Sahu 2012; Smithers PIRA 2016; Freedonia Group 2019; Smithers 2020).

The single-use wipes market is broken down into four segments: household (32%), baby (31%), industrial (19%), and personal care (18%) (Fig. 1B). Consumer wipes include household, baby, and personal care wipes, making up approximately 80% of the market. The household segment includes all wipes used for cleaning and disinfecting surfaces in homes. Personal care wipes include, but are not limited to, cleansing wipes for hands and face, makeup removing wipes, moist bathroom tissue, and feminine hygiene wipes. Baby wipes are most often used to clean babies' skin but are also used as personal care wipes by all ages. The consumer wipes segment is driven by cost, convenience, hygiene, performance, ease of use, time savings, disposability, and safety (Zhang 2010a; Smithers PIRA 2016). Industrial wipes include a range of cleaning products sold to manufacturers, health care providers, commercial institutions, and businesses. The industrial wipes

segment is driven predominantly by cost, performance, and safety of the products (Smithers PIRA 2016).

Market Segment Prices

For this market study, the unit prices of 250 single-use wipe products were tabulated, as shown in Fig. 2. Products were segmented by the market breakdown described above. Consumer wipe prices were recorded from three online retail stores: Amazon, Walmart, and Shoppers Drug Mart. Industrial wipe prices were taken from the online retail stores Amazon and Canadian Tire, as well as multiple industrial supplier websites (Fisher Scientific 2020; Grainger Canada 2020; PMG Supply: Facility & Site Supply Solutions 2020; Roxton Industries 2020; VWR 2020; Wurth 2020). The prices were recorded during the month of November 2020 and do not include taxes or shipping costs.

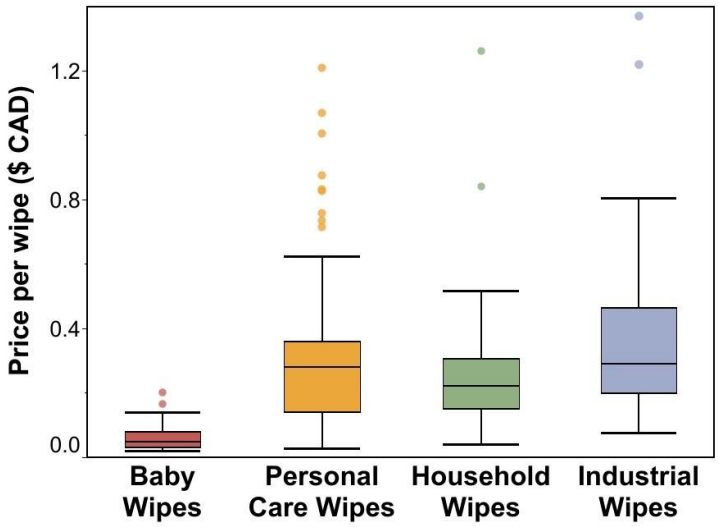

Fig. 2. Unit price of 250 wipes taken from Canadian online retail stores and supplier websites during November 2020. The box and whisker plot shows the range of product prices. The box represents the 2nd and 3rd quartile with the whiskers extending to the 1st and 4th. The line in the middle of the box represents the median, and the dots are the outliers.

Baby wipes are the least expensive segment with an average price of 6 cents per wipe. Premium baby wipes, for example those reported as being made from "natural" ingredients, are sold at a higher retail price.

The personal care segment ranges in price because it includes a variety of products for different uses. Premium personal care wipes are marketed as the following: flushable wipes, wipes containing natural ingredients, wipes that are gentler on skin, and wipes that target specific demographics that would not normally purchase wipes (*e.g.*, "Dude Wipes") (Freedonia Group 2019).

The household disinfecting wipes have an average unit price of 28 cents per wipe. The range in cost of disinfecting wipes is not indicative of premium products but rather the type of brand, where independent brands have a higher price on average and private label brands cost less.

The industrial wipes have the widest price range (7 cents to $1.50 per wipe) because they have a large variety of end uses and supply channels. For example, some healthcare cleaning products are available at low costs through industrial suppliers whereas other technical wipes used in automotive care are sold in smaller packs at higher prices.

Emerging trends in the market are related to increasing consumer concerns with environmental sustainability and health. These concerns are driving wipe manufacturers to use a higher proportion of natural materials, increase flushability (*i.e.*, compatibility with sewer systems), adopt more ingredient transparency, and create gentler formulations for personal care and baby wipes (Zhang 2010a; Freedonia Group 2019).

Market Trends

A few manufacturers and brands dominate the wet wipes market, namely Procter & Gamble Co., Kimberly-Clark Corp., Nice-Pak, and Rockline (Zhang 2010a; Freedonia Group 2019). However, private labels and brands that offer "subscribe and save" options are increasing in market share (McIntyre 2016). In the US wipes market, private labels accounted for 34% of the market share in 2018 (Kusnic 2020). Private labels are becoming more popular because they can provide similar or higher performing products at a lower price than competing national brands (Kusnic 2020; Zambrano *et al.* 2020). Companies that offer "subscribe and save" products are also increasing in popularity due to the convenience of recurring deliveries of trusted products combined with savings.

Market sizes and growth in different regions are driven by economic factors of the three largest markets, *i.e.*, North America, Western Europe, and Asia, and are continuing to grow (Steed and Smithers PIRA 2018). The smaller South and Central American and Eastern European markets are also expected to grow due to an increasing population who have disposable income and are more likely to purchase convenience products such as wipes (Steed and Smithers PIRA 2018).

The COVID-19 pandemic and the rising popularity of e-commerce are altering the usage share of personal care, household, and industrial wipes across the global market. COVID-19 has changed how consumers use and view single-use wipes. Historically, baby wipes have been the largest segment within the industry, but this domination will be challenged in the coming year as consumers are now diligently using disinfectant wipes to reduce exposure to COVID-19. Moving forward, household disinfecting and healthcare wipes are likely to see the largest increase in demand and will require supply chains to react with agility and adaptability. E-commerce platforms allow consumers to easily access information on a wide selection of wipes to compare their quality and pricing. Over the next year, consumers are expected to opt for convenience-based services, such as e-commerce, that make purchasing non-essential items like wipes much easier.

Certain types of personal care wipes are forecasted to grow in the short term. Flushable baby wipes are gaining traction with consumers due to recent concerns around the environmental impact of single-use wipes. Consumers (incorrectly) assume that wipes labeled as flushable will disintegrate and biodegrade in the same fashion as toilet paper. Non-flushable adult moist tissues and cosmetic face masks have also gained popularity with the introduction of innovative products that are marketed as luxury beauty and personal care items (Sahu 2012). These items are non-essential but have become convenient self-care items for consumers on a budget. Unfortunately, the convenient use of wipes introduces a whole new set of environmental, economic, and social challenges.

MAJOR CHALLENGES

To understand where the most promising opportunities lie for single-use wipes, the major challenges of their use and disposal must be addressed. This section outlines the three pillars of sustainability and the challenges faced in each area surrounding single-use wipes.

Environmental Challenges

Single-use wipes can be as environmentally damaging as any other single-use product. Wipes are most likely disposed of in the garbage, or down the toilet if they are labelled as "flushable." Unfortunately, depending on the material composition and specific disposal conditions, the wipe may persist in the natural environment for hundreds of years (Allen 2016). Compounding these environmental issues, consumers often dispose of single-use wipes improperly. A 2017 study found that 78% of the solids found in the wastewater system in Berlin, Germany, consisted of nonwoven materials (Mitchell *et al.* 2017). Commonly known as "fatbergs", these solid masses that accumulate in the sewer system are caused by an accretion of porous nonwoven materials with foreign materials and FOGs (fat, oil, and grease). These materials cause blockages and clog pumps in sewer systems and wastewater treatment plants. Nonwovens have become such a common occurrence in wastewater systems that wastewater operators must regularly manually remove wipes and other nonwovens from sewer screens. Solids collected from these events are sent to the landfill, where they contribute to the general environmental problems associated with landfill waste, including the generation of microplastics (Mitchell *et al.* 2017; Ó Briain *et al.* 2020).

The term biodegradability is often used to market single-use wipes as being more eco-friendly. The term biodegradable refers to a product that degrades into an environmentally benign end-product in nature (*e.g.*, not under landfill conditions), where exposure to light, moisture, and oxygen is typically presumed. The first flushable wipes, introduced in 2006, were made of nonbiodegradable plastic nonwoven materials. Since 2013, many brands have replaced plastics with regenerated cellulose fibres such as lyocell and viscose. Their biodegradation is slow and temperature-dependent in natural water environments (McGivern 2019). Cellulosic fibres have better environmental outcomes compared to plastic; however, when disposed of, most wipes do not reach an environment where biodegradation can take place. If flushed properly through better infrastructure requirements to prevent blockages, cellulosic fibers will make it to a wastewater treatment plant and biodegrade.

Modern flushable wipes consist of only cellulosic fibres, usually a blend of wood pulp cellulose and RC. However, consumers often flush other types of wipes, especially baby wipes, which contain plastic fibres. Abrasion of these materials in the sewer system releases microplastics into the natural environment, which are harmful to animal and human health (Karapanagioti and Kalavrouziotis 2019; Ó Briain *et al.* 2020). Wastewater treatment removes some of these harmful particles, but an estimated global average of 19.2 microplastic particles per L of effluent are released into the marine environment (Karapanagioti and Kalavrouziotis 2019). Indirectly, wipes disposed of into landfills may also release microplastics into the natural environment upon degradation.

Economic Challenges

While the environmental costs of single-use wet wipes are obvious, the economic costs are mostly hidden. The upfront cost of wipes to the consumer is low, usually costing a few dollars per package. Improper disposal or nonideal plumbing conditions may lead to blockages when wipes are flushed, and consumers are, either directly or indirectly through taxes, responsible for the cost of repairs. These costs can total thousands of dollars for homeowners or millions of dollars for municipalities. Metro Vancouver estimates they spend $100,000 every year to unclog regional pumping stations (Metro Vancouver 2017). The Municipal Enforcement Sewer Use Group estimates that more than $250 million is spent annually in Canada to address sewer issues caused by wipes (Westcott 2018).

Social Challenges

Consumer behaviour

Despite the environmental and economic costs, consumers value the convenience of single-use wipes and are therefore unlikely to stop using these types of products. Alongside low purchase prices and convenience, consumers expect wipes to have certain features, such as softness, strength (*i.e.*, no "poke-through"), natural ingredients, and absorbency. Manufacturers constantly strive to improve upon these features to remain competitive in the wipes market. With consumers becoming more conscious of the negative effects of single-use plastics, wipe manufacturers have adapted by using biodegradable materials in their wipes. Wipes manufacturers are meeting this demand by switching to a higher natural fibre content in flushable wipes, which poses a considerable challenge as the tensile strength decreases with increased natural fibre content. The challenge manufacturers face is finding a balance of wipe strength when in use and disintegration when flushed.

The challenge with introducing more environmentally friendly wipes is that consumers will not have an incentive to use them unless they match or exceed existing brands' level of quality, accessibility, and, most importantly, price.

Policy and regulation

There is great confusion and poor consumer education about what materials are flushable. Often many non-flushable wipes and other products (*e.g.*, dog waste bags, food waste) are found in sewer systems. A field study by the Association of the Nonwoven Fabrics Industry (INDA) in 2012 found that 91% of the items collected from pump station inlet screens were non-flushable items such as baby wipes, napkins, feminine hygiene products, and household wipes (Nice-Pak 2017). Currently there are few jurisdictions with regulations and standards for the labelling of single-use wipes. Such policies will require wipes manufacturers to clearly label their products as "do not flush" unless they meet industry guidelines for flushability. The creation of an international standard for flushability would ensure manufacturers produce wipes that are truly flushable. However, passing this type of legislation is an ongoing challenge due to disagreements between wastewater professionals and nonwoven manufacturers. Further regulations on the materials that can be used in single-use wipes may help reduce the environmental impact of all wipes. For example, certain regions, such as the EU and Canada, are currently evaluating bans on single-use plastic items, including certain types of single-use wipes (The European Parliament and the Council of the European Union 2019; Environment and Climate Change Canada 2020).

STRATEGIES TO ADDRESS CHALLENGES

Industry Guidelines and Code of Practice

In North America, there are currently no regulations governing the methods and labeling of products that can be marked flushable or non-flushable. The labeling Code of Practice (COP) was developed by the INDA and the European Disposables and Nonwovens Association (EDANA) in collaboration with several clean water and wastewater agencies (EDANA 2018). The COP was designed for nonwoven wipe producers to clearly label products that have a high potential to be discarded *via* the toilet as "Flushable" or "Do Not Flush."

The testing methods adopted by most major nonwoven manufacturers were developed in conjunction with the INDA and EDANA. The 4th Edition of the Guidelines for Assessing the Flushability of Disposable Nonwoven Products (GD4) (EDANA 2018) is based on three main principles: wipes should clear toilets and pipes, wipes should pass through wastewater treatment (WWT) systems without causing problems, and wipes should disintegrate, or completely dispersed in water, to be unrecognizable in effluent leaving WWT systems (EDANA 2018). To be considered flushable, a wipe must pass seven tests, designed to simulate its path after flushing. Failure of one test would require the product to be labeled "Do Not Flush" with INDA's symbol (Fig. 3) displayed prominently on its packaging. However, a perfect score is not required to pass a test. For example, producers can choose between two different biodegradability tests, one of which stops at 70% biodegradability of the wipe (EDANA 2018), leaving a lot of flexibility for manufacturers when designing wipes.

Fig. 3. Association of the Nonwoven Fabrics Industry "Do Not Flush" symbol

Wastewater professionals have formed organizations, such as the International Water Services Flushability Group (IWSFG) and have created their own publicly available specification (PAS) documents for flushability. The IWSFG Flushability Specifications utilize some of the testing methods and labelling guidelines from the INDA and EDANA, but overall are a more comprehensive assessment of "flushable" products. The three PAS documents together give an in-depth, stringent evaluation of what products should be deemed "flushable." The IWSFG considers environmental protection by addressing the composition of fibres in the nonwoven wipe. In addition, it has modified INDA and EDANA tests to account for a variety of different WWT plants, as not all municipalities have the same treatment systems. There was an effort by an International Organization for Standardization (ISO) technical committee to create a standard for flushable products. However, it was reduced to a technical report. The IWSFG, a group of wastewater

professionals, was formed after this failure to develop their own technical specifications. Without an international standard, many countries are trying to implement their own regulations, and manufacturers may struggle to produce materials that meet regulations in every country where they sell wipes. Region specific regulations could make it difficult for manufacturers to develop flushable wipes that meet standards in all countries. With access to e-commerce, this could cause confusion and improper disposal among consumers.

Consumer Education Campaigns

Many major players who produce flushable wipes have created educational consumer campaigns on "responsible flushing." Utilities and municipalities are also doing their part in educating consumers on what can be flushed by investing in educational campaigns that urge consumers to avoid disposing of wipes in the toilet. Generally, these campaigns are effective while they are active, but utilities have observed that consumers tend to forget the messaging once the campaign is over. Many municipalities and utilities lack the funds to run long-lasting campaigns and therefore struggle to achieve consistent widespread impact. Since 2016, Metro Vancouver has run "The Unflushables" campaign, urging the public to only flush the three P's (*i.e.*, poo, pee, and toilet paper).

TECHNICAL PROPERTIES

Although there is some variation in the desired properties of the wipe depending on its intended end use, virtually all single-use wet wipes must have high strength, high absorbency, and in the case of flushable wipes, high dispersibility when introduced into the sewer system (*i.e.*, 80% of the initial dry mass of the wipe must pass through a 25-mm sieve after 30 min as per the IWSFG PAS (IWSFG 2018)). This section outlines the required technical properties and material composition of wet wipes, as summarized in Fig. 4. The ideal single-use wipe would be completely and rapidly biodegradable and made from 100% renewable feedstocks.

Single-use wipes must have relatively high mechanical strength to prevent failure of the nonwoven material during use and dispensing. Strength may refer to wet strength, when the wipe is saturated with a moistening liquid or lotion, or it may refer to the dry strength. For wet wipes, dry strength is an important consideration for disposal, as a high dry mechanical strength will prevent wipes from physically disintegrating easily when disposed of in a landfill or composting facility. Likewise, high wet strength in sewer conditions can lead to blockages. Wipes must also have high enough absorbency to hold the moistening liquid but be able to release it upon the application of mild pressure during use. For flushable wipes, high dispersibility is important to ensure that the nonwoven substrate degrades rapidly and to a sufficient extent to prevent blockages in home or municipal sewer systems. Currently, toilet paper is considered by many organizations to be the only truly flushable product, as it disintegrates quickly when wet and degrades rapidly in all sewer systems. This is related to its affinity to completely disperse in water. For a single-use wipe to be considered truly flushable, given the same conditions, it should disperse exactly like toilet paper. Other material properties may be important for end use, such as softness, flexibility, and resistance to linting. Although the properties and performance of a wipe depend on the nature of all components, the nature of the fibres used is most important.

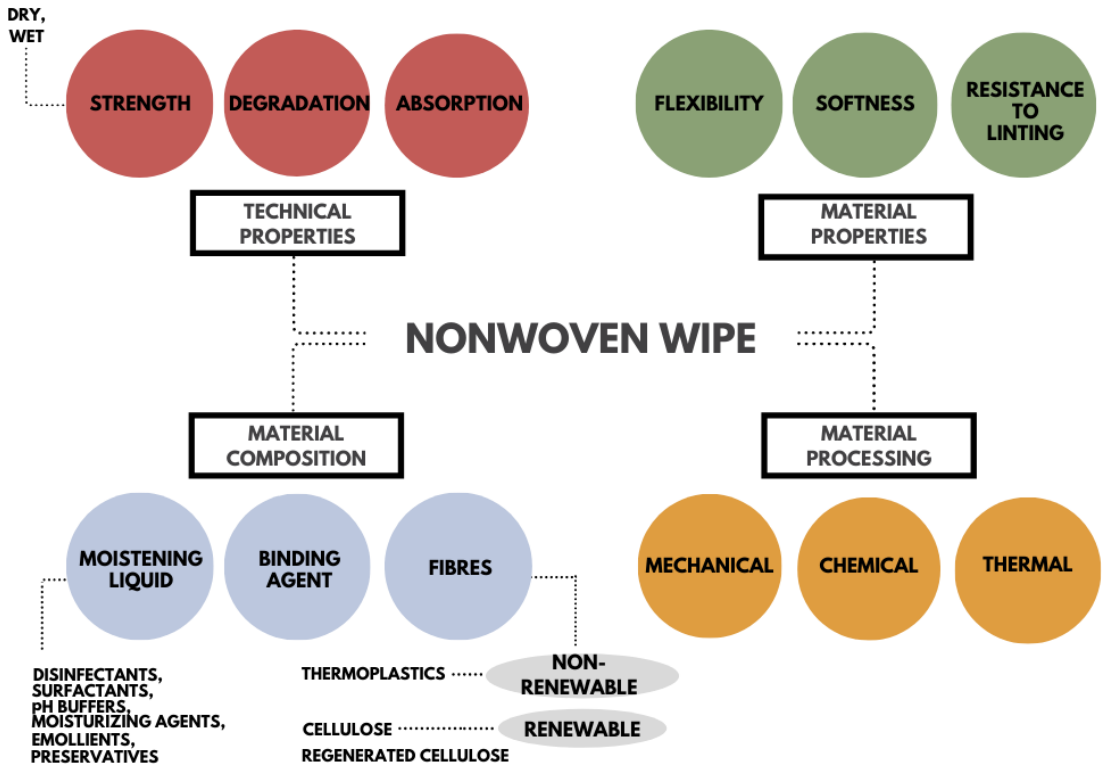

Fig. 4. Summary of technical status and key properties of wet wipes

Fibres are thin filaments that are used to construct nonwovens and can be varied in source. A nonwoven sheet may contain a blend of different fibre types, usually a non-renewable thermoplastic fibre, such as polyethylene or polypropylene, and a cellulosic fibre derived from plant biomass, such as wood pulp. This combination is often used, as thermoplastics are inexpensive and provide tensile strength while cellulosic fibres provide high absorption (Song *et al.* 2019). The drawback is that wipes containing non-renewable plastic fibres are not biodegradable. Unmodified cellulose may be used directly, but RC is often used due to its improved absorbency and mechanical strength (Atasağun and Bhat 2018). In addition to the chemical identity of the fibres, their size and shape, length, aspect ratio, roughness, and degree of entanglement with other fibres contribute to the properties of the nonwoven sheet. Longer, rougher fibres lead to better entanglement and, therefore, higher mechanical strength. Shorter fibre lengths (*i.e.*, < 1 cm) (Tipper 2018) are favoured for flushable wipes, as they are more dispersible in sewer systems.

The individual fibres in a nonwoven material may be held together by the entanglement of the fibres during production, the addition of binder fibres, or by use of a binding agent. Hydroentanglement, a process where high pressure water jets are used to tangle together the fibres, is commonly used to achieve binding. Flushable wipes are often made dispersible *via* ion- or pH-sensitive cationic polymer binders. These binding agents form strong but reversible bonds within the wipe when soaked in the moistening liquid (*i.e.*, high ionic strength or acidic pH), but the bonds break when the wipe is disposed of (*e.g.*, down the toilet) and the moistening liquid is heavily diluted. The wipe then loses its wet strength and begins to disintegrate (Adams and Reinke 1976; Atasağun and Bhat 2018). According to wastewater professionals, to pass through the sewer system, the wipe

must disintegrate rapidly (*i.e.*, within minutes rather than hours) and into small enough (< 1 in) pieces that will not cause clogs.

The composition of the moistening liquid depends on the specific type of wipe. Common active ingredients in household and hospital disinfectant wipes include alcohols, chlorine compounds (*e.g.*, bleach), aldehydes, peroxygens, and quaternary ammonium compounds (Song *et al.* 2019). Personal care wipes, including baby wipes, make up wipes, and feminine hygiene wipes, are moistened with dilute aqueous solutions of cleansers (surfactants), moisturizing agents, pH buffers, emollients, and preservatives (Vongsa *et al.* 2019).

CHALLENGES AND OPPORTUNITIES

The key technical challenges associated with single-use wipes relate to the material. Non-flushable wipes (and some flushable wipes) contain thermoplastic fibres and do not fully biodegrade, and therefore must be disposed of in a landfill (Durukan and Karadagli 2019). Only some flushable wipes disintegrate in sewer systems, where insufficient disintegration can lead to clogs (Durukan and Karadagli 2019). The main issue is related to inappropriate flushing of non-biodegradable items and flushing in large quantities, which can cause blockages. These challenges may be solved by technological improvements to the nonwoven material and its constituent fibres. Renewable fibres that have sufficient strength and absorbency may take the place of thermoplastic fibres and poorly dispersible RC. Strength may be improved by increased fibrillation and entanglement of existing fibre types, or by the development of novel regeneration methods for cellulose, resulting in strong but dispersible fibres. Innovations in nonwoven production (*e.g.*, incorporation of combinations of fibre types and sizes, improvements to the fibre entanglement process) may lead to better, more sustainable wipe materials. Furthermore, it may be possible to introduce new functionalities into the nonwoven substrates. For example, bioactive components may be added for improved disinfection, or a colourimetric sensor responsive to a specific microbe or chemical contaminant could be incorporated into the nonwoven substrate. Bio-based binding agents that fail rapidly in disposal conditions could also lead to higher dispersibility, and therefore, flushable wipes would become less damaging to sewer infrastructure.

Additionally, product design improvements may prove to be paramount. Wet wipes are shipped in their moistening liquid, requiring a high wet strength to withstand storage and use, increasing shipping weight, and possibly drying out after an individual package is opened by a consumer. Innovative dispenser designs where the wipes and moistening liquid are separated until immediately before use have been suggested (Zhang 2010b). Refills of wipes and moistening liquid may be supplied separately, and the liquid may be supplied at a higher concentration for dilution by the end user to reduce shipping weight. Fohm Co. designed a hands-free dispenser for a moistening solution that effectively turns toilet paper, a truly flushable material, into a wet wipe. This solution bypasses the need for a strong nonwoven substrate and the subsequent problems with disposal. Innovative disposal methods and systems that bypass sewer systems and landfills may also lessen the environmental impact of wipes.

CONCLUSIONS

Disposable single-use wipes present an environmental, technical, and social challenge. With wet wipes becoming increasingly popular due to COVID-19 and more accessible because of the rise in e-commerce or, more broadly, due to global affluence, the disposal challenge is paramount. How can developers of future products reduce the environmental impact of single-use wipes that often contain plastic or high strength cellulosic materials? Consumer education through better labelling and legislation may have a role, because, despite current labelling guidelines, many nonwovens must still be removed from wastewater treatment plants and sent to the landfill. While targeting the consumer directly may help, certain technical improvements to nonwoven wipes could reduce the environmental impact and lead to the development of better wipes.

The ideal, sustainable solution to these challenges includes a bio-based nonwoven substrate that can be used in all wipe applications, including flushables and non-flushables. The ideal wipe should also be designed to have the least environmental impact at its end-of-life, whether that involves a home or industrial composting system, a sewer, or, if necessary, a landfill. To disrupt the current marketplace, a new material would need to perform equally to all other wipes in terms of performance (*i.e.*, strength, absorption, dispersion in water, softness, flexibility, and resistance to linting) and cost (Fig. 5A). Figure 5B shows a summary of potential technical and non-technical improvements that could drive innovation to move from the current status quo to the ideal wipe.

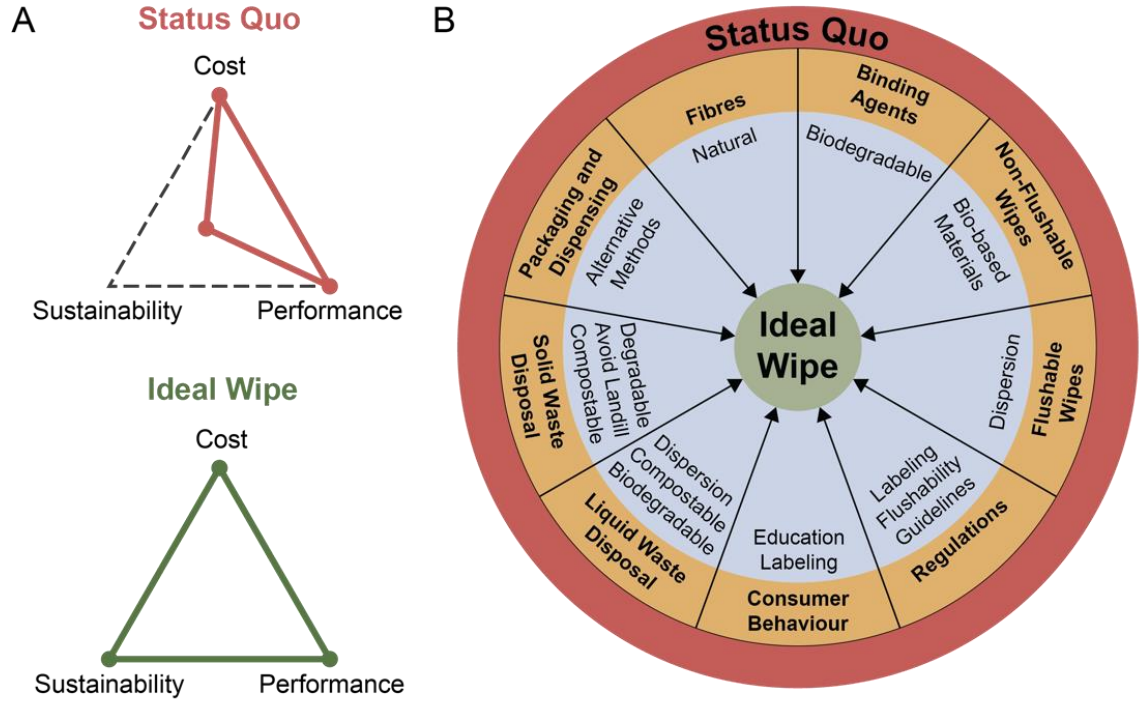

Fig. 5. (A) A comparison of the three main evaluation criteria (*i.e.*, cost, performance, and sustainability) for wipes made under the current status quo and for wipes made with an ideal material; (B) summary of current challenges and opportunities for innovative wet wipes

Widespread adoption of a novel nonwoven material by manufacturers presents a significant challenge, particularly if it is not compatible with current production infrastructure. However, the adoption of bio-based nonwoven wipes is predicted to grow as policies and regulations banning the use of single-use plastics in wipes are being brought forth in legislatures around the world. This situation puts bio-based materials in a favorable position to meet upcoming market demands. Alternatively, design solutions could reduce environmental impacts, and bioproducts could be the base of functional materials that have yet to be seen in the wet wipes industry.

Beyond disposable wipes, innovations in bio-based nonwoven materials have considerable potential to improve the environmental outcomes of all nonwoven products in a variety of applications. Applications including filtration devices, medical supplies, and personal protective equipment, such as respiratory masks, have all seen increased use since the onset of the COVID-19 pandemic. These materials often incorporate non-renewable materials, and their increasing use is only intensifying the issues associated with single-use plastics. Sustainable nonwoven substrates, even if initially developed for wet wipes, have the potential to disrupt the nonwovens industry at large.

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