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Development of antimicrobial yarn by recycled cotton based yarns and chitosan staple fibers

Desarrollo de hilos antimicrobianos a base de algodón reciclado y
fibras de quitosano

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Abstract

The project provides information on how to reduce the environmental impact of textiles through the recycling of conventional garments and fabrics through processes of reusing recycled cotton fibers. The development of the new recycled product is improved by adding different concentrations of chitosan staple fiber for an antimicrobial and therapeutic effect to improve the health of the user.

The experimental part of the project shows the steps of the prototypes of the recycled antimicrobial yarn produced with mixtures of fibers of recycled cotton and chitosan, as well as its parametric analysis of the thread suitable to be woven in any weaving machine. Finally, the project remarks the reduction of environmental pollution by conventional methods of textile production, and removes dyeing and finishing processes using recycled colored fibers.

Key Words: Recycled cotton yarn, chitosan staple fiber, ecological yarn, antimicrobial yarn, environment friendly textile, chitosan blended yarn.

Resumen

El proyecto proporciona información de como reducir el impacto ambiental textil mediante el reciclaje de prendas y tejidos convencionales por procesos de reutilización de fibras recicladas de algodón. El desarrollo del nuevo producto reciclado es mejorado añadiendo diferentes concentraciones de fibra cortada de quitosano para que actúe con un efecto antimicrobiano y además con un carácter terapéutico para mejorar la salud del usuario.

La parte experimental del proyecto muestra los pasos de elaboración de los prototipos del hilo reciclado antimicrobiano producidos con mezclas de fibras de algodón reciclado y quitosán, así como su análisis de parametría del hilo apto para ser tejido en cualquier maquina de tejeduría. Finalmente el proyecto ratifica la disminución de la contaminación ambiental por métodos convencionales de producción textil, eliminando procesos de tintura y acabado ya que utiliza fibras de recicladas de color.

Palabras Claves: *Hilos de algodón reciclado, quitosano fibra cortada, hilos ecologicos, hilos antimicrobianos, hilos mezclados de quitosano.*

1. INTRODUCTION

At all times each human being is a carrier of microbes (fungi and bacteria), when they come into contact with clothing or household textiles, they can grow and multiply, thus converting textiles into the path or route for the transfer to other people and initiating the transmission of infections that could take us to the hospital.

Microbial growth, especially that bacteria in textile materials, can cause fabric deterioration, development of bad odors, irritation of the skin and infection.

At an international level, this area has been very studied, and research works based on **Chitosan**, and nanoparticles of silver and metal oxides such as ZnO and CuO stand out.

The textile industry is challenged by the presence of microorganisms and the negative effects they cause. The deterioration, disfigurement and bad odors are undesirable effects that are produced from the microbial contamination of the textile. In antimicrobial agents, chitosan polymers used for a fiber production. **Chitosan is available in staple fiber** form and fir to use in yarn spinning.

In recent years a large amount of research work has been developed around textiles with antimicrobial finishes, not only with the aim of reducing transmission of infectious diseases and improving the quality of life of human beings, but also to protect the textile in itself against the damages generated by mold, fungi or rot caused by other microorganisms. In other words, the growth of microorganisms in textile fabrics leads to functional, hygienic and aesthetic difficulties. Most of the organisms that cause problems are fungi (discoloration, color spots and damage to fiber) and bacteria (bad odors, stains and viscous sensation). And often both develop a symbiotic relationship in the textile.

The properties of highly hydrophilic cotton, non-toxic and its softness make cotton a very attractive option as a biocompatible textile surface for garments and biomedical materials.

Textiles functionalized with antimicrobial nanoparticles and fibers reduce and inhibit the growth of various microbes, therefore we managed to interrupt the route or route of transfer of them, avoiding and controlling the increase of home and intra-hospitalary infections.

The global demand for textile products is steadily increasing, a trend likely to continue due population growth and economic development. Meanwhile, the textile industry is facing tremendous environmental and resource challenges. Sixty-three percent of textile fibers are derived from petrochemicals whose production and fate give rise to considerable carbon dioxide (CO₂) emissions. The remaining 37% is dominated by cotton (24%), a thirsty plant associated with water depletion e the desiccation of the Aral Sea being the most infamous example and toxic pollution, due to intensive use of pesticides. For most categories of environmental impacts, later stages in the textile production process give rise to even larger impacts. Wet treatment processes (dyeing, finishing, printing, etc.) are major sources of toxic emissions and spinning of yarns and weaving/knitting of fabrics most often rely on fossil energy use, causing emissions such as CO₂ and particulates. **Water use, toxic chemicals and waste are the main environmental issues facing the textile industry.** Estimated that, for several environmental impact categories, the impact per garment use in a western country (in this case, Sweden) must be reduced by 30-100% by 2050 if the industry is to be considered sustainable with regard to the planetary boundaries outlined. Such a grand transition requires

a combination of different measures for impact reduction, most likely including **more reuse and recycling**.

As the world moves towards more an eco-friendly and sustainable production, the fashion and apparel industry also in the path, by producing organic material. This research is focused on recycling the waste fabric into fibers. The main aim is to develop new apparel product by using recycled fiber, yarn, fabrics by combining chitosan fibers. For this purpose, the cutting waste from the knitted garment manufacturing industries was collected and utilized for the recycling process. It was found that the fabrics had a reasonable amount of physical characteristics like dimensional stability, bursting strength, pilling and abrasion resistance. The fabrics were made into casual garments and cost-effectiveness study also performed on the developed garments. The results were promising that the **developed garments from recycled cotton fibers are cheaper than the garments developed from normal raw materials and a plus, with antimicrobial properties**. It is also double-advantageous for the manufacturers by providing some earning out of the waste and also solves waste management and disposal issues.

2. OBJECTIVE

In this research we will use recycled cotton fibers which obtained by mechanical processes as environment friendly materials and staple fibers of chitosan to produce yarns with conventional spinning methods. **Production of the open-end yarn samples will be made with the determined percentages of recycled cotton fiber and antimicrobial chitosan staple fibers** for their analysis after productions. It will be the combination of environment friendly fibers which we can use in fabric production for all kind of use.

After develop a novel **antibacterial yarn made by recycled cotton with chitosan staple fiber** with standard technical properties also will be analyzed the usability of the developed yarns instead of the yarns used in knitting and weaving.

The aim of this research is giving **more usage to the green materials** (recycled) in our routine life by combining with value added new textile fibers. Actually recycled textile fibers are used in many of textile sub-sectors like clothing production, home textile, automotive textile, geotextile, etc. We reuse recycled cotton fibers daily as T-shirts, towels, bed sheets, upholstery. But the producers of these products do not prefer to add green textile labels in their products and the reason may be that the consumers thinks about hygiene.

In last years, the tendency of green textile is increasing and some clothing brands also started to add these labels which certificate that they use recycled fibers in their products and they care for the environment. But still the consumers would be worried for pollution and hygiene. Use of detergents and chemicals is an option to give guarantee of cleanness but if we really care for the environment without contaminate the water we can **solve the pollution problem** by using anti-microbial and eco-friendly textile fibers.

3. STATE OF ART

3.1. Structure of the Textile Industry

The majority of chemical use in textile production occurs during 'wet processing', i.e., in dyeing, washing, printing, and fabric finishing. Textile dyeing and finishing mills use considerably more water—as much as 200 tons of water for every metric ton of textiles produced.

Many of the chemicals used in textile production are non-hazardous, and only a relatively small proportion is potentially hazardous. However, in absolute terms, quite a large number of hazardous chemicals are used in textile production because of the very large number of chemicals deployed (1).

For example, the Swedish Chemical Agency has estimated that there are over 10,000 substances which can be used in dyeing and printing processes alone, about 3,000 of which are commonly used. The availability of such a large number of chemicals for use by industry poses obvious difficulties when it comes to sharing and maintaining information about them, as well as drawing up and enforcing regulations for their use (2).

The global textile supply chain is complex, involving many different stages and people. Multinational brand owners may contract suppliers directly or indirectly, through agents or importers. Normally it is the brand owner who triggers the product development process, including research and design. Brand owners are therefore best placed to bring about change in the production of textiles and clothing through their choices of suppliers, the design of their products, and the control they can exert over the use of chemicals in the production process and the final product (3).

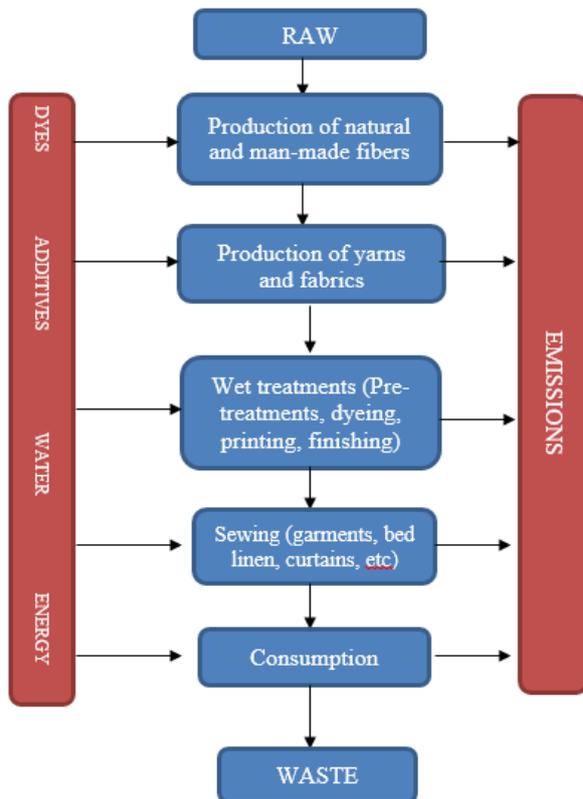


Figure 1- Textile product chain

A simplified textile product chain is shown in Figure 1 (4). For LCI analyses, environmental data and process inputs and outputs have to be collected. The major participants in the textile and clothing supply chain are multinational brand owners, raw material suppliers, textile and clothing producers, financiers, retailers, and customers.

Companies are sometimes responsible for more than one link in the supply chain; for example, the brand owner and retailer may be the same company, or the brand owner may have its own in-house production chain. The complexities of the supply chain inevitably lead to lack of transparency about the various steps involved in the manufacture of products and their potential environmental impacts (5).

3.1.1. Pollution and Textile Manufacture

A recent survey (3) of 15,000 people in 15 countries, across both the northern and southern hemispheres, found that the water scarcity and water pollution are two top environmental concerns of the world's population. China has some of the worst water pollution in the world, with as much as 70 % of its rivers, lakes, and reservoirs being affected, and the textile industry, an important sector of China's economy, with more than 50,000 textile mills in the country, contributes to this pollution. Building upon investigations by Greenpeace International, the report 'Dirty Laundry' profiles the problem of toxic-water pollution that results from the release of hazardous chemicals by the textile industry in China, water pollution which poses serious and immediate threats to both ecosystems and human health.

The investigations forming the basis of this report focus on wastewater discharges from two facilities in China. Significantly, hazardous and persistent chemicals with hormone-disrupting properties were found in the samples.

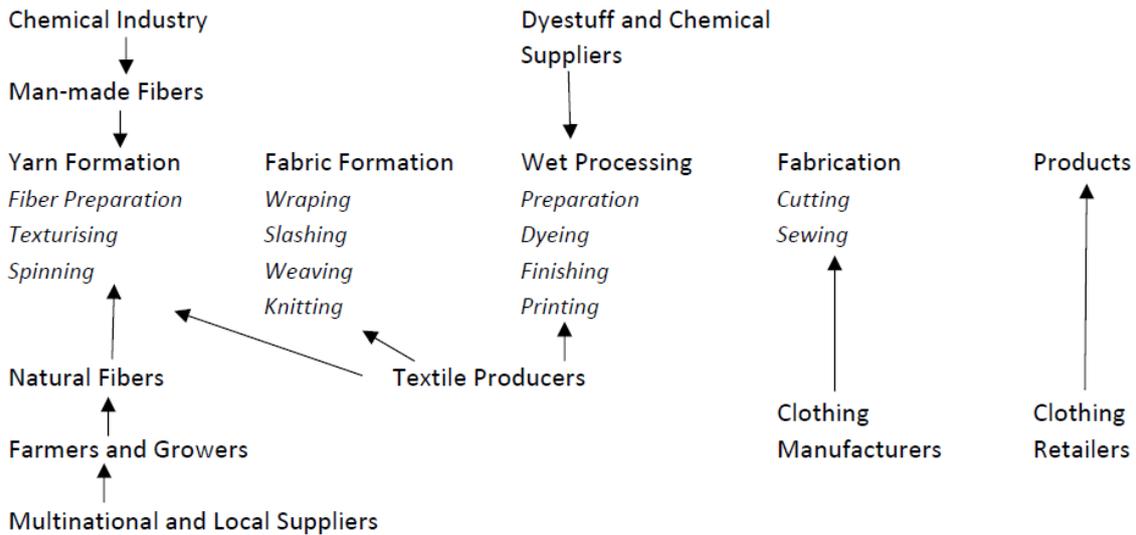


Figure 2 - The businesses involved in the textile and clothing supply chain

Alkylphenols, including nonylphenol (NP), were found in wastewater samples from both facilities, and perfluorinated chemicals (PFCs), in particular perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate, were present in the wastewater from the Youngor Textile Complex, despite the presence of a modern wastewater treatment plant. The two facilities have commercial relationships (as suppliers) with a number of other Chinese and international brands (6).

New research commissioned by Greenpeace International (7) shows that residues of the hazardous chemicals NP ethoxylates (NPEs)—used in textile manufacturing—remain in many clothing items sold by major international clothing brands and, when washed, a significant percentage of the chemicals in these clothes is released and subsequently discharged into rivers, lakes, and seas, where they turn into the even more toxic and hormone-disrupting chemical NP.

The Institute of Public and Environmental Affairs, a leading environmental nongovernmental organization (NGO) in China, has released the second in a series of exposures about the severe water pollution problems caused by textile dyeing and finishing in China. (8).

The modern textile industry has migrated from one region or country to another. Most of this migration has been driven by one factor, the need to cut costs. Although large-scale pollution from the textile industry has been a problem throughout its history, the more recent use of persistent and hazardous chemicals poses a greater, and often invisible, threat to ecosystems and human health.

Referring to all industries, the United Nations Environment Program stated: ‘Worldwide, it is estimated that industry is responsible for dumping 300–500 million tons of heavy metals, solvents, toxic sludge and other waste into waters each year’ (9). When considering both the volume generated and the effluent composition, textile wastewater is considered to be the most polluted of all the industrial sectors (10); with a complex global textile supply chain, involving many different stages and often several companies, brand owners may therefore be the best placed to bring about the required change.

Launched in July 2011, the Detox campaign (11), introduced by Greenpeace International, has exposed links between textile manufacturing facilities causing toxic water pollution in China and many of the world’s top clothing brands.

3.1.2. Sustainability in Textile Manufacture

The textile industry has been cited as the most ecologically harmful industry in the world (12), whilst an argument said that water pollution is a major issue in China and that its textile industry, a large water user, has traditionally experienced wastewater problems (13). In some cases, wastewaters are discharged (largely untreated) into groundwater with extreme pH values and temperatures as well as high chemical loading.

The following areas have the potential to make the life cycles of textiles and clothing unsustainable (14):

1. Use of toxic chemicals
2. Consumption of water
3. Consumption of energy
4. Generation of waste
5. Air emissions
6. Transportation
7. Packing materials

3.1.2.1. Usage of Chemicals

About 25 % of the global production of chemicals is used in the textile industry globally (15). As many as 2000 different chemicals are used in textile processing, especially in textile wet processing, and many of these are known to be harmful to human (and animal) health. Some of these chemicals evaporate, some are dissolved in treatment water which is discharged into the environment, and some are retained in the fabric. A list of the most commonly used chemicals, some of which are involved in fabric production, and linked to human health problems varying from annoying to profound, have been published by the National Institute for Environmental Health Sciences (part of the US Department of Health and Human Services) (16).

The chemicals causing particular concern when released into the environment display one or more of the following properties:

- Persistence (they do not readily break down in the environment)
- Bio-accumulation (they can accumulate in organisms, and even increase in concentration as they work their way up a food chain)
- Toxicity

Chemicals with these properties are described as PBTs (persistent, bio-accumulative, and toxic substances). Organic chemicals with these properties are sometimes referred to as persistent organic pollutants (POPs). Despite initial dilution in large volumes of water or air, such pollutants can persist long enough in the receiving environment to be transported over long distances, to concentrate in sediments and organisms, and some can cause significant harm even at what may appear to be very low concentrations.

Volatile chemicals pose particular problems because they evaporate into the air or are absorbed into foods or through the skin. Some chemicals are carcinogenic or may cause harm to children, even before birth, while others may trigger allergic reactions in some people. Some reporters predict that the 5–10 % of the population allergic to chemicals will grow to 60 % by 2020 (17).

Various toxicity-reduction evaluations in North Carolina, conducted between 1985 and 1995, found recurrence of compounds identified as toxic agents (18), many of which were related to wet processing. A short, non-exhaustive list of such toxic compounds is given in Table 1.

<i>Name of toxic chemical</i>	<i>Used as/in</i>
<i>Tri-butyl tin oxide (TBTO)</i>	Biocide on hosiery and fabrics
<i>Non-ionic surfactants</i>	Detergents in textile preparation and dyeing
<i>Sodium chloride</i>	Cationic surfactants Textile dyeing and finishing
<i>Sodium sulfate</i>	Dyeing of cotton textiles
<i>Copper</i>	Dyeing of cotton and polyamide; in its elemental, non-complexed form, it is toxic

Table 1 - List of a few popular but toxic textile chemicals and their fields of application

Non-ionic surfactants pose a particular problem. Surfactants slow to degrade cause acute and chronic toxicity effects. Understanding their rate of biodegradability is a key factor in the treatment of effluents, as the only available options are either longer treatment times or substituting more rapidly degradable surfactants. It is estimated that there are over 500 unique non-ionic surfactants used in textile processing, and environmental data are scarce for these compounds. NPs and nonylphenol ethoxylates have been restricted in the EU as a hazard to human and environmental safety.

Sodium chloride and sodium sulfate, which are used as exhausting agents in the direct dyeing of cotton, also present a particular problem. These substances are particularly problematic in areas where the natural flows in the receiving streams were very small in relation to the discharge flows of the POTW. There still remains no practical treatment to remove these salts from textile wastewaters and, thus far, the only way to resolve the issue has been to dilute the effluent. The problem can, however, be minimized by using low-salt reactive dyes or adopting pad application methods. Copper was found to be present in many blue and black dyes with 'free,' noncomplexed copper acting as the immediate toxic agent; hence, their screening and the development of copper-free dyes was encouraged.

Even after eliminating several specific toxic compounds, there still remain a large group of textile chemicals called wet-processing auxiliaries. These 'namebrand' products are composed of complex mixtures of surfactants, softening agents, solvents, chelating agents, and water-based polymers. Most of these products are mixtures designed to perform a certain task in the preparation, dyeing, or finishing of textiles. Because of both the huge variety and different concentrations of chemicals which can be used in these products, there are significant difficulties in identifying the components of these mixtures, a problem exaggerated as producers keep the ingredients a trade secret.

3.1.2.2. Consumption of Water

Clean water is both essential to the planet's ecosystems and fundamental to people's well-being. It is a basic human right. Waterways such as rivers and lakes supply communities with vital resources, including drinking water, water for crop irrigation, and foods such as fish and shellfish. These waterways also serve as a support system for industrial activity, providing water for many manufacturing and cooling processes. However, such industrial activities can affect water quality and thereby jeopardise the other resources which rivers and lakes provide. Globally, water resources are being degraded by the increasing pressure of human activities.

Economic and population growth places ever-greater demands on water supplies, reducing the quantity and quality of water available for wildlife, ecosystem function, and human

consumption. Clean water is a finite resource which is becoming scarce, and it is used at every step of the wet-processing sequence both to convey the chemicals into the material and to wash them out before the beginning of the next step. Once charged with chemical additives, the water is expelled as wastewater, which, if untreated, may pollute the environment thermally by virtue of the high temperature of the effluent, extreme pH, and/or contamination with dyes, diluents of dyes, auxiliaries, bleaches, detergents, optical brighteners, and many other chemicals used during textile processing (19).

Problems become worse when there is inappropriate or incomplete effluent treatment or a discharge of polluted water directly without treatment, leading to polluted surface waters and polluted aquifers, i.e., layers of earth or rock containing water (20). As a result, any heavy metal constituents in effluents lead to pollution with both negative ecological impacts on the water-body environment and deterioration of human health.

The textile and related industries are considered by some to be the second highest consumer and polluter of clean water next to agriculture (19). The textile services sector is an essential adjunct to the textile industry and is needed to manufacture, finish, market, and distribute the products; the services related to the textile industry include computer-aided design, contract quilting, contract yarn spinning, custom printing, fabric welding, silk screen printing, textile designers services, contract knitting, contract sewing, custom embroidery, custom slitting, pleating, specialty weaving, contract napping, contract weaving, custom perforating, custom swatching, private labeling, testing of the end product, etc. (21).

Water is used in various steps during the textile dyeing process both to convey the chemicals used during the step and to wash them out before the beginning of the next step. In a traditional dyeing and finishing operation, for example, 1 ton of fabric could result in the pollution of up to 200 tons of water by a suite of harmful chemicals and, in the process, consumes large amounts of energy for steam and hot water. With the industry now centered in countries with still-developing environmental regulatory systems, such as China, India, Bangladesh, and Vietnam, textile manufacturing continues to have a huge environmental footprint. Some commonly observed routes of wastage of water (19) are:

- Excessive use of water in washing
- Poor housekeeping measures such as broken or missing valves
- Unattended leaks through pipes and hoses
- Instances when cooling waters are left running even after shutdown of the machinery
- Use of inefficient washing equipment
- Excessively long washing cycles
- Use of fresh water at all points of water use

The reutilization of wastewater can present very important savings, namely in reduction of water, energy, and chemical consumption. The recycling of wastewater is effected in process baths and rinsing waters, before fresh water is taken for treatment for removal of remaining chemicals and other effluents generated. Steam condensate and cooling water are easily recoverable as they are clean and recovery of their thermal energy can very quickly pay back the investment.

Techniques and technologies of implementing energy management, including heat recovery, in the use of steam in the textile industry vary extensively in terms of the scope of their application, their costs, and their benefits. The case of the textile dyeing and finishing industry in Mauritius has been investigated thoroughly by Elahee (22) energy management was applied to optimize the use of steam in dyeing and finishing plants. The state of energy management in

the dyeing and finishing industry had similarities with that of its European or North American counterparts before the oil crisis of the 1970s. The dyeing and finishing industry in Mauritius consumed about 35,000 tons oil equivalent annually for steam generation, mostly in the form of fuel oil and coal. The potential reduction in fossil fuel consumption was about 35 % in small textile dyeing and finishing plants and 25 % in large ones. Out of the latter, 15 and 10 %, respectively, of the fossil fuel consumption can be saved with heat recovery, that is, essentially with low cost, short payback energy-saving measures.

Quality, productivity, and response time gains as well as environmental benefits are significant. If properly applied, the overall payback for investment in such technology can be reduced to not more than 2 years. However, investing in such technology is not without risks, particularly in view of the fact that these are not easily set up in developing countries. In almost all cases know-how transfer and ancillary costs should be duly considered. The progress of such technology should also not be at the expense of indigenous techniques and technologies.

Heat recovery, in particular, improves profitability and competitiveness on the international markets. Reduced reliance on imported fossil fuel is achievable, hence keeping the industry safe from rising oil or coal prices. The reduction in global and local pollution is also an important benefit. This will help to make the textile industry a pillar of sustainable development of these countries, many already producing high quality raw materials. Consequently, their chances of pursuing socioeconomic progress coupled with environmental protection will be much improved.

Pattanapunt et al. (23) studied how to recover heat waste from boiler exhaust gas by mean of a shell and tube heat exchanger. By processing the exhaust gas from the boiler dyeing process, which carries a large amount of heat, energy consumption can be decreased by using waste-heat recovery systems.

Wastewater Pollutants

In the future, water is set to become an increasingly scarce and therefore extremely valuable resource. Demand for water is growing at more than twice the rate at which the world's population is growing. Over the past 100 years, the world's population has increased threefold, while water consumption has risen by a factor of seven. Since 1970, the available amount of water per capita has been reduced by 40 % as a result.

It takes approximately 2,500–3,000 L of water to manufacture a single cotton shirt. The bulk of this water is required to grow the cotton, followed in second place by the wet finishing process. The first consequences of water shortages and wastewater problems are already starting to be felt in the textile finishing industry.

3.1.2.3. Consumption of Energy

The textile industry is a major energy-consuming industry with low efficiency in energy utilization. About 23 % of the total energy used is consumed in weaving, 34 % in spinning, 38 % in chemical processing, and another 5 % for miscellaneous purposes. Thermal energy dominates in chemical processing, being used mainly for heating water and drying textile materials, whilst electrical power dominates the energy consumption pattern in spinning and weaving (24).

Energy is one of the main cost factors in the textile industry. Especially in times of high energy price volatility, improving energy efficiency should be a primary concern for textile plants, and various energy-efficiency opportunities exist in every textile plant, many of which are cost-effective but not implemented because of limited information or high initial cost.

Electricity is the main energy consumed in the textile industry, being used for driving machinery, cooling, temperature control, lighting, and office equipment, whereas fuel oil, liquefied petroleum gas, coal, and city gas are widely used to generate steam.

Spinning consumes the greatest share of electricity (41 %) followed by weaving (including weaving preparation) (18 %), whereas wet-processing preparation (desizing, bleaching) and finishing together consume the greatest share of thermal energy (35 %). A significant amount of thermal energy is also lost during steam generation and distribution (35 %), but these percentages vary from plant to plant.

Such analysis of energy efficiency improvement opportunities in the textile industry points to advantages to be gained from retrofit/process optimization, not just from complete replacement of current machinery with state-of-the-art new technology (25). Table 2 shows the average values for thermal energy use in dyeing plants in Japan (25), indicating the proportion of thermal energy use for each step in a dyeing plant, and where the potential exists for the greatest energy efficiency gains. The table also gives useful information about where losses are most significant, which losses should be addressed first, and the general means of reducing the losses.

There are various possibilities for using renewable energy in the textile industry examples are:

1. Installation of wind-powered turbo-ventilators on production plant roofs
2. Use of direct solar energy for fiber drying
3. Use of solar energy for water heating in the textile industry
4. Solar electricity generation

<i>Thermal energy consumed for</i>	<i>% Share</i>	<i>Required action to reduce heat loss</i>
<i>Heating of product</i>	16.6	
<i>Drying of product</i>	17.2	Avoid over-drying
<i>Heat loss of waste liquor</i>	24.9	Recovery of waste heat
<i>Heat loss from equipment</i>	12.3	Improved insulation
<i>Heat loss with exhaust</i>	9.3	Reduction of exhaust gas
<i>Heat loss from idle equipment</i>	3.7	Stop energy supply during idle time
<i>Heat loss from evaporation</i>	4.7	Use covered equipment
<i>Heat loss with unrecovered condensate</i>	4.1	Optimize recovery of condensate
<i>Heat loss during recovery of condensate</i>	0.6	
<i>Others</i>	6.6	
<i>Total</i>	100	

Table 2 - Average thermal energy use in dyeing plants of Japan

3.1.2.4. Generation of Waste

As with any other industry, the textile industry generates all categories of industrial wastes, namely liquids, solids, and gases. For greener processes, nonrenewable wastes need to be recycled and renewable wastes need to be composted if recycling is not an option. Various useful materials can be recovered from textile process wastes.

The recovery of chemicals such as sodium hydroxide from mercerization baths is achievable by heating to concentrate the solution; following such a step, 90 % of the sodium hydroxide can

be recovered (26). The EVAC vacuum suction system in the textile dyeing process recovers hot alkaline hydrogen peroxide, additives, and finishing chemicals.

3.1.2.5. Air Emissions

Burnt fossil fuels contribute to the emissions of carbon dioxide, a primary contributor to the greenhouse effect. Textile manufacture is also responsible for the following emissions:

- Nitrogen oxides and sulfur oxides (from fossil-fuel-heated boilers) which create acidity in the natural environment (freshwater lakes, rivers, forests and soils) and lead to the deterioration of metal and building structures. They also contribute to smog formation in urban areas.
- Solvent escaping into the air from drying ovens used in solvent coating operations.
- Solvents released from cleaning activities (general facility clean-up and maintenance, print screen cleaning).
- Emissions of volatile hydrocarbons which include non-methane hydrocarbons (NMHCs) and oxygenated NMHCs (e.g., alcohols, aldehydes, and organic acids).

Transportation

Long-distance transport is required to move the finished products from the factories located in low-labor-cost countries to the consumer in a developed country, thus adding to the overall quantity of non-renewable fuel consumed.

Packaging Materials

Packaging is the science, art, and technology of enclosing or protecting products for distribution, storage, sale, and use. Packaging also refers to the process of design, evaluation, and production of packages. Packaging can be described as a coordinated system of preparing goods for transport, warehousing, logistics, sale, and end use. Packaging contains, protects, preserves, transports, informs, and sells (27).

For consumer packaging, the packaging used to present products in stores, materials often used are plastic, paper, metal, aluminum, cotton, hemp, and biodegradable materials. Companies implementing eco-friendly actions are reducing their carbon footprint by using more recycled materials, increasingly reusing packaging components for other purposes or products, and employing recycled materials (e.g., paper, cotton, jute, hemp, wood), biodegradable materials, natural products grown without the use of pesticides or artificial fertilizers, and reusable materials (e.g., cotton bags or hemp). Reducing packaging waste is one of the best ways to minimize environmental impact.

3.1.2.6. Non-Eco-Friendly Substances

The terms 'environmentally friendly,' 'eco-friendly,' 'nature friendly,' and 'green' are used to refer to goods and services, laws, guidelines, and policies claimed to inflict minimal or no harm on the environment (28). 'Green' is a very subjective term which could be interpreted in different ways, but whatever the definition, becoming green is important in that it means having made a commitment to protecting people and the planet; green or eco-friendly goods, services, and practices assure the use of environmentally-friendly materials, free from harmful chemicals, compounds, or energy waste, which do not deplete the environment during production and transportation, whereas non-eco-friendly substances, such as non-biodegradable organic materials and hazardous substances, may do harm to the environment.

3.1.2.7. Non-Biodegradable Organic Materials

A non-biodegradable material is a substance which is not broken down by microorganisms, has an oxygen demand only if it is a chemical reducing agent, but has no biochemical oxygen demand (BOD) (29). BOD is the amount of dissolved oxygen needed by aerobic biological organisms in a body of water to break down organic materials present in a given water sample at a specified temperature over a specific time period. The BOD value is most commonly expressed in milligrams of oxygen consumed per liter of sample during 5 days of incubation at 20C and is often used as an indicator of the degree of organic pollution of water.

3.1.2.8. Hazardous Chemicals

As defined by the Occupational Safety and Health Administration under the US Department of Labor Standard 1910.1200 (29), a hazardous chemical is one which is a health hazard or a physical hazard. Being designated as a health hazard means that there is statistically significant evidence that acute (short-term) or chronic (long-term) health effects may occur in humans exposed to that particular substance.

The term 'health hazard' includes chemicals which are carcinogens or otherwise toxic or highly toxic agents, which damage the lungs, skin, eyes, or mucous membranes. A chemical is designated as a physical hazard when there is scientifically valid evidence that it is a combustible liquid, a compressed gas, explosive, flammable, organic peroxide, oxidizer, pyrophoric, unstable (reactive), or water reactive.

On the basis of chemical behavior, therefore, hazardous substances may be categorized as combustible and flammable substances, oxidizers, reactive substances, or corrosive substances, but perhaps the greatest concern is with toxicity. Toxic heavy metals and volatile organic compounds (VOCs) are two important sub-groups of hazardous substances.

3.1.2.9. Toxic Metals/Heavy Metals

With regard to toxicity, differentiation between metals depends upon the chemical properties of the metals and their compounds and upon the biological properties of the organisms at risk, and heavy metals are some of the most harmful ecologically. In the case of humans, they may enter the body through food, water, or air, or by absorption through the skin, and exhibit a tendency to bio-accumulate, with many forming lipid-soluble organo-metallic compounds which accumulate within cells and organs, thereby impairing their functions. The health hazards associated with some heavy metals and metalloids (e.g., arsenic) are listed in Table 3 (30).

Heavy metals are inherently persistent and some of them (for example cadmium, lead, and mercury) are also able to bio-accumulate and/or are toxic.

Although they occur naturally in rocks, their use by industry can release them into the environment in quantities that can damage ecosystems. Heavy metal compounds do not break down into harmless constituents but can react to form new compounds.

<i>Metal/metalloid</i>	<i>Associated health hazard</i>
<i>Lead (Pb)</i>	Damage to the brain, nervous system, and kidneys
<i>Mercury (Hg)</i>	Damage to the brain
<i>Cadmium (Cd)</i>	Disorders of the respiratory system, kidneys, and lungs
<i>Chromium (Cr)</i>	Skin and respiratory disorders, ulceration of skin and cancer of the respiratory tract on inhalation

Some types of toxicity make it difficult to define 'safe' levels for substances, even at low doses, for example, substances may be:

- Carcinogenic (causing cancer), mutagenic (able to alter genes), and/or reprotoxic (harmful to reproduction)
- Endocrine disruptors (interfering with hormone systems)

Some possible sources of heavy metals in textile operations are incoming fiber, water, dyestuffs (heavy metals are constituents of some classes of dyes and pigments), auxiliaries, finishing chemical impurities, and the plumbing fittings used in dyeing and finishing plants. Heavy metals may also be found in plant fibers because of absorption from the soil in which they are grown. Once absorbed by humans, heavy metals tend to accumulate in internal organs such as the liver or the kidneys with serious effects on health, particularly when high levels of accumulation are reached.

Heavy metals enter the environment through wastewaters from different branches of the textile industry, in particular from discharged spinning baths, from man-made fiber manufacturing plants, and from effluents discharged from dyeing machines. However, although it contributes, the textile industry is not the only source of this type of pollution; significant amounts of heavy metals enter the environment in many cities from vehicle emissions, and solid industrial wastes also contribute to contamination. Several other sources contribute to trace metal impurities, such as:

- Natural levels in our environment
- Impurities in reactants or raw materials
- Use of metal catalysts or reactants
- Corrosion of manufacturing plant equipment

Limits on heavy metal content do not apply to products containing a listed metal as an inherent part of the molecular structure or formula such as metal complex dyes (31).

3.1.2.10. Toxic Volatile Organic Compounds

VOCs are organic chemicals with a high vapor pressure under normal atmospheric conditions. Their high vapor pressure results from their low boiling points causing large numbers of molecules to evaporate and enter the surrounding air. An example is formaldehyde, with a boiling point of $-19\text{ }^{\circ}\text{C}$, which will steadily evaporate unless kept in a closed container.

Anthropogenic VOCs are regulated by law, especially in indoor applications, where the concentrations can potentially become the highest, whereas unregulated VOCs from substances such as citrus oils and terpenes may still have the ability to develop an unpleasant reaction in chemically-sensitive people. VOCs are typically not acutely toxic, but instead often display compounding long-term health effects.

Some VOCs, such as styrene and limonene, can react with nitrogen oxides or with ozone in the atmosphere to produce new oxidation products and secondary aerosols, which can cause sensory irritation symptoms. Unspecified VOCs are said to be important in the creation of smog (32).

3.1.2.11. Conventional Solvents

Most organic solvents are volatile and, unless controlled, will escape into the workplace and the atmosphere, where they can be instrumental in causing photochemical smog. Many hydrocarbon and oxygenated solvents readily evaporate and are highly flammable. Hence, their use needs to be managed carefully to minimize the risks of fire or explosion, particularly during loading and unloading for storage or transport, during storage itself, and when being used in bulk. Safe handling information provided by the supplier should be carefully followed.

Chlorinated Solvents

Dry cleaning is any cleaning process for clothing and textiles using a chemical solvent other than water and is often used for delicate fabrics or those in which the dye shows low wet-fastness. The most widely used solvent is tetrachloroethylene, also known as perchloroethylene or PERC. PERC is classified as carcinogenic to humans by the EPA and effluents must be handled as a hazardous waste, so, to prevent contamination of drinking water, dry cleaners must take special precautions.

Glycol ethers (dipropylene glycol tert-butyl ether) (Rynex, Solvair, Lyondell Impress) are in many cases more effective than PERC and in all cases more environmentally friendly. Dipropylene glycol tert-butyl ether (DPTB) has a flashpoint far above current industry standards, yet at the same time possesses a degree of solvency for water-soluble stains at least equivalent to, and in most cases better than, PERC and the other glycol ether dry-cleaning solvents presently in commercial use. A particular advantage of the DPTB—water solutions in dry cleaning is that they do not behave as a typical mixture but, rather, the behavior is that of a single substance. This permits a better defined separation than azeotropic distillation at a lower boiling point, facilitating reclamation more effectively (at a level of 99 % or greater), and also enhancing purification using conventional distillation techniques.

The silicone fluid, decamethylcyclopentasiloxane or D5, is gentler on garments than PERC and does not cause color loss. Although considerably more environmentally friendly, its price is more than double that of PERC as it is licensed by GreenEarth Cleaning which charges an annual affiliation fee.

Chlorinated solvents such as trichloroethane (TCE) are sometimes used by textile manufacturers to dissolve other substances during manufacturing and to clean fabrics. TCE is an ozone depleting substance which can persist in the environment. It is also known to affect the CNS, liver, and kidneys. Since 2008 the EU has severely restricted the use of TCE in both products and fabric cleaning.

Chlorobenzenes are persistent and bio-accumulative chemicals. They have been used as solvents, biocides, in the manufacture of dyes, and as chemical intermediates. They commonly affect the liver, thyroid, and CNS. Hexachlorobenzene (HCB), the most toxic and persistent chemical of this group, is also a hormone disruptor. Within the EU, pentachlorobenzene and HCB are classified as ‘priority hazardous substances’ under regulations requiring measures to be taken to eliminate their pollution of surface waters in Europe. They are also listed as ‘persistent organic pollutants’ for global restriction under the Stockholm Convention and, in line with this, they are prohibited or scheduled for reduction and eventual elimination in Europe (33).

Sr. No	Name	Sr. No	Name	Sr. No	Name
1	Acetic Acid	7	Tetrahydrofuran	13	Dimethyl ether
2	Acetophenone	8	Diethylene glycol	14	Glycerol
3	Benzyl Benzoate	9	Dimethyl sulfoxide	15	Hexane

4	Tert Butanol	10	Dimethyl ether	16	Methanol
5	Diethylene glycol	11	Ethyl acetate	17	Polyglycol E 200
6	Dibutyl ether	12	Ethylene glycol	18	Propylene glycol

Table 4 - A few safe and green solvents

The safe or green solvents recommended by Ash and Ash are listed in Table 4. Solvents produced from renewable resources such as ethanol produced by fermentation of sugar-containing feedstock, starchy materials, or lignocellulosic materials may be selected. This substitution for petrochemical solvents leads to an avoidance of the use of fossil resources (petrochemicals) and fossil-fuel related emissions of CO₂ into the environment.

3.1.2.12. Eco-Friendly Substitutes

The characteristics of green chemicals are as follows:

- Prepared from renewable or readily-available resources by environmentally friendly processes
- Low tendency to undergo sudden, violent, unpredictable reactions such as explosions
- Non-flammable or poorly flammable
- Low toxicity and absence of toxic constituents, particularly heavy metals
- Biodegradable
- Low tendency to undergo bio-accumulation in food chains in the environment. (34)

3.1.2.13. Cleaner Production

As part of the cleaner production approach, a textile processor has to be lean, efficient, and innovative, which can be achieved by the following ways: (35)

- Lean: good housekeeping, conservation and control
- Efficient: 'right-first-time' (RFT) approach, chemical/water/energy/machine audits, optimization/rationalization
- Innovative: reuse, recovery and recycle initiatives for process change.

3.2. Environmental Impact Areas in the Textile and Clothing Industries

The broad classification of environmental impact areas of the textile and clothing industries is shown in Figure 3. (36)

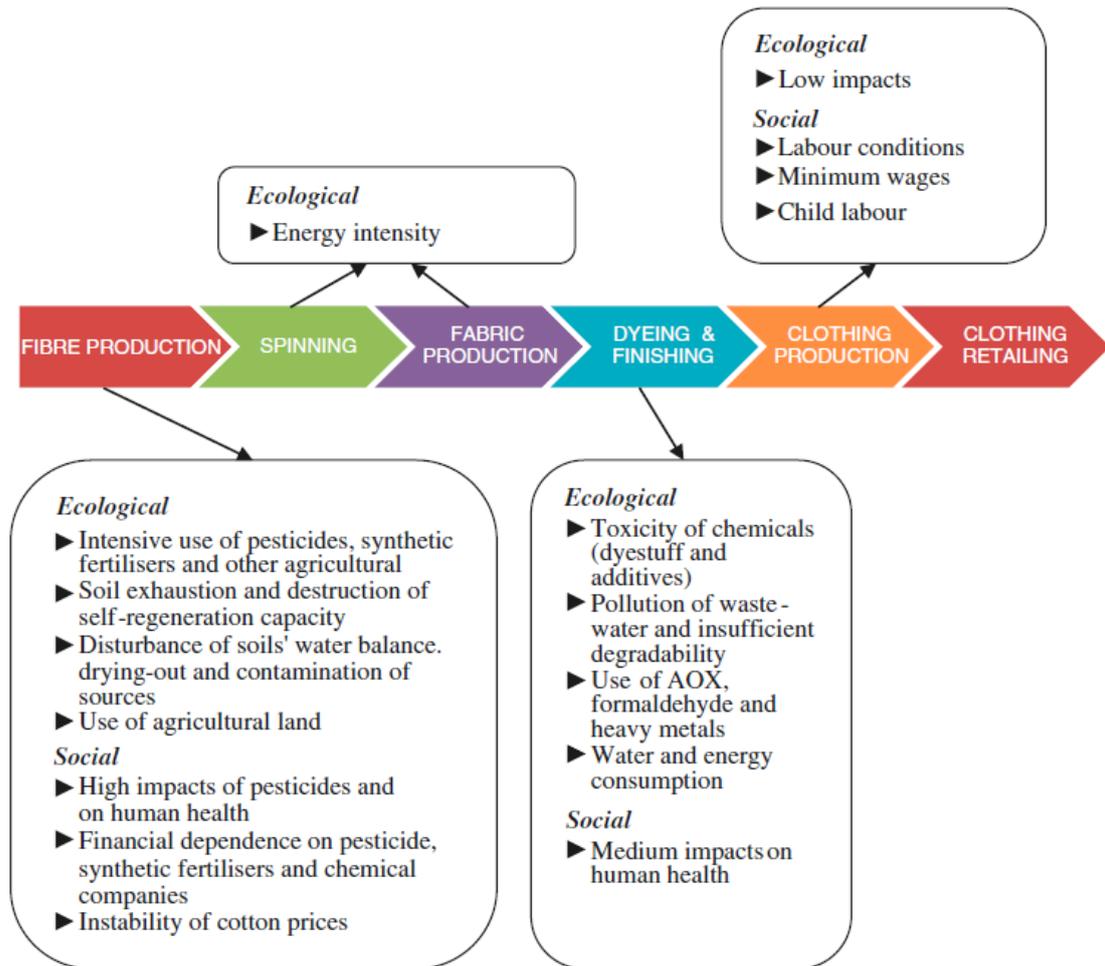


Figure 3 - Environmental and social impact of textile manufacturing processes

The sustainability challenges facing a retailer are not limited to a retailer’s operational impacts. As discussed, the majority of these sustainability challenges are associated with their products and their supply chains. But other impacts are associated with the product after it has been purchased by the consumer. It is now common to consider the sustainability of a retailer in a much wider context that reflects the life cycle of their products.

The product life cycle considers not just the impacts created through the sourcing of materials, the manufacturing process, and the impacts associated with retail operations such as logistics and warehousing, it also incorporates the “use” phase of products and the impact of the disposal of the product at the end of its life. Figure 4 is an example of a product life cycle, and it is a representation of the energy use for each of the key stages of a typical apparel product:

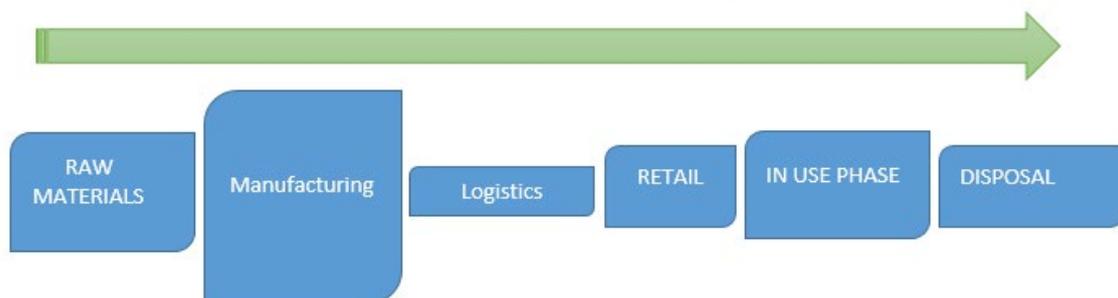


Figure 4 - A representation of energy use across a product life cycle.

Raw materials: Energy use to extract or grow the raw materials. For polyester this could include the energy required to extract and refine the crude oil used to produce ethylene, one of the base molecules for polyester fiber. Or it could include the energy consumption for the production of nitrogen fertilizers used in cotton cultivation.

- *Manufacturing:* Consumption of energy for textile processes such as ginning, spinning, weaving, dyeing, and garment production.
- *Logistics:* Related to the energy needed to transport the finished goods from the manufacturer to the retailer.
- *Retail operations:* Energy consumption by the head office, warehouses, stores, and local logistics functions of the retailer.
- *Use phase:* For clothing this generally refers to the energy consumption for washing, drying, and ironing.
- *Disposal:* The energy balance for this stage is determined by the disposal option used, which can include reuse, recycling, incineration, or disposal to a landfill. In the case of incinerated garments there could be a potential positive impact in terms of energy production if incineration is part of an energy recovery system.

In general, the magnitude of impacts associated with raw materials, the manufacturing processing, and logistics are controlled by suppliers, whereas the scale of impacts attributed to the use phase and disposal are determined by the consumer. The retailer has direct control of the energy impacts associated with the retail operations, assuming they own the stores and they are not operating a concession or franchise model.

By using this type of analysis, retailers and others have been able to show the life-cycle impacts for various products and from this, hot spots or points of significant impact within the life cycle have to be identified. Hot spot analysis is an important way to identify where retailers should make their investments to maximize the results. For example, consider Figure 5, which is a representation of the typical water-consumption impacts for a clothing product. From this we can see that a significant proportion of the water consumption is associated with the raw materials and the manufacturing process. Some retailer analysis has shown these two stages of the life cycle represent up to 99% of the water impact. If a retailer does not perform this type of “hot spot” analysis, the retailer may spend thousands of dollars on water-saving devices within the “retail” stage of the life cycle but only be able to influence just 1% of the overall water use. Through analysis of the product life cycle and identifying hot spots it would be better to consider investments in water-saving strategies for the supply chain where there is a much larger opportunity to save water.

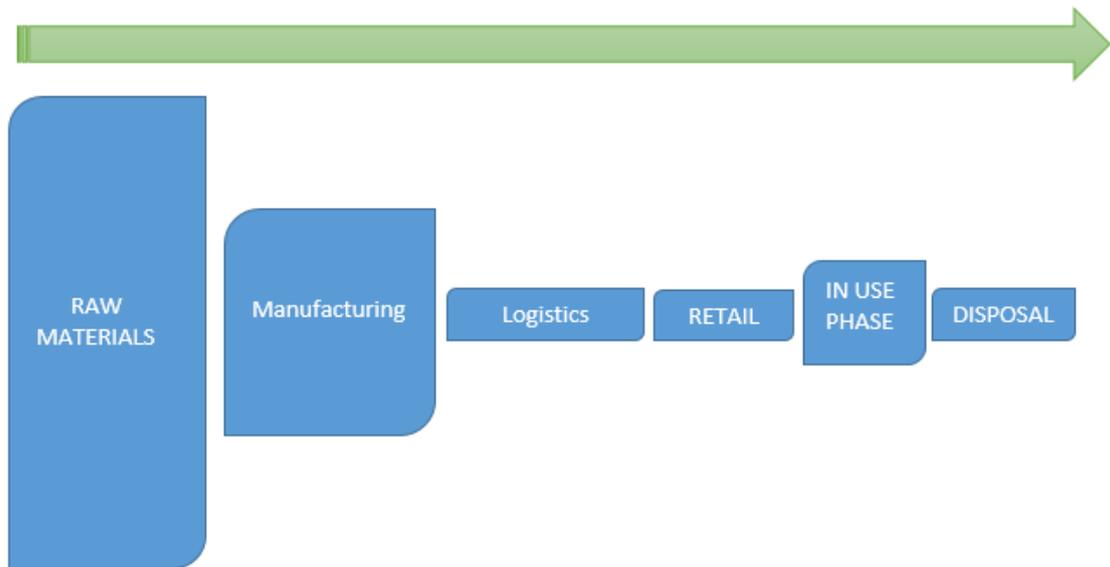


Figure 5 - A representation of water use across a product life cycle.

Figures 4 and 5 are simple representations of a single sustainability impact or dimension, in this case, energy use and water use. But there are a multitude of different impacts categories, such as green gas emissions, toxicological loading, eutrophication, land use, and more that need to be considered to fully evaluate the sustainability of a retailer. Hot spot analysis can be used to assess impacts for a large number of sustainability categories for individual products and for the whole of the retailer's portfolio of operations. However, whether the analysis is done at a product level or organizational level, a deep understanding of the life cycle is required.

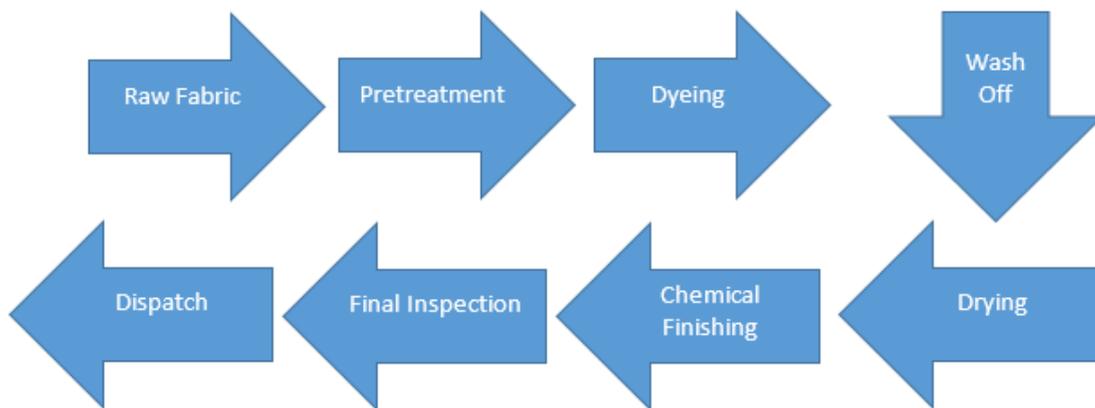


Figure 6 - phase of the life cycle

The third hot spot for water consumption is the "use" phase of the life cycle. The magnitude of water use at this stage is determined by the number of times the consumer washed the product. For a retailer to establish the full life-cycle water footprint of one cotton T-shirt he or she would need to know where the cotton was grown, the chemicals, processes, and equipment used in the dyeing process and how many times the consumer washed the product; considerable knowledge about the extended supply chain and consumer behavior is needed to complete the analysis. The complexity of the assessment process is even more challenging

when the social and ethical aspects of sustainability are considered. What level of data granularity is required to understand the social standards of one factory compared to another, or how the animal welfare standards for sheep farming in Australia compared to sheep farming in South Africa?

And for the coloration example, the social dimensions such as working conditions, exposure to harmful chemicals and labor rights would need to be assessed for the workers and the community surrounding the dyehouse. (37)

3.2.1. Raw Materials

The choice of raw materials for clothing has large impacts on the environment. Natural fibres such as cotton are often assumed to be a more environmentally responsible choice, but this is not necessarily true. Cotton is notorious for its intensive use of water and pesticides. The same goes for “natural” dyes, which depend on the harvest of millions of insects or plant bark to achieve colour the “natural” way. These dyes often also require the use of supplementary chemicals containing toxic metals. Fibre choice also drives consumer-care requirements, which can indirectly impact the consumption of water, energy and toxic chemicals.

3.2.2. Manufacturing

Textile dyeing and finishing mills are particularly high-volume, high-impact producers of water pollution and carbon dioxide emissions. Through extensive hands-on research in China, NRDC (Natural Resources Defense Council) has developed ten practical, easy-to-implement best practices for textile mills which significantly reduce water, energy and chemical use, thereby improving manufacturing efficiency. In fact, all of NRDC’s best practices for responsible sourcing pay themselves back in less than a year. Designers, retailers and brands can reduce the footprint of their global supply chain by encouraging or requiring mills to adopt these improvements and reward those who do so with more business. (38)

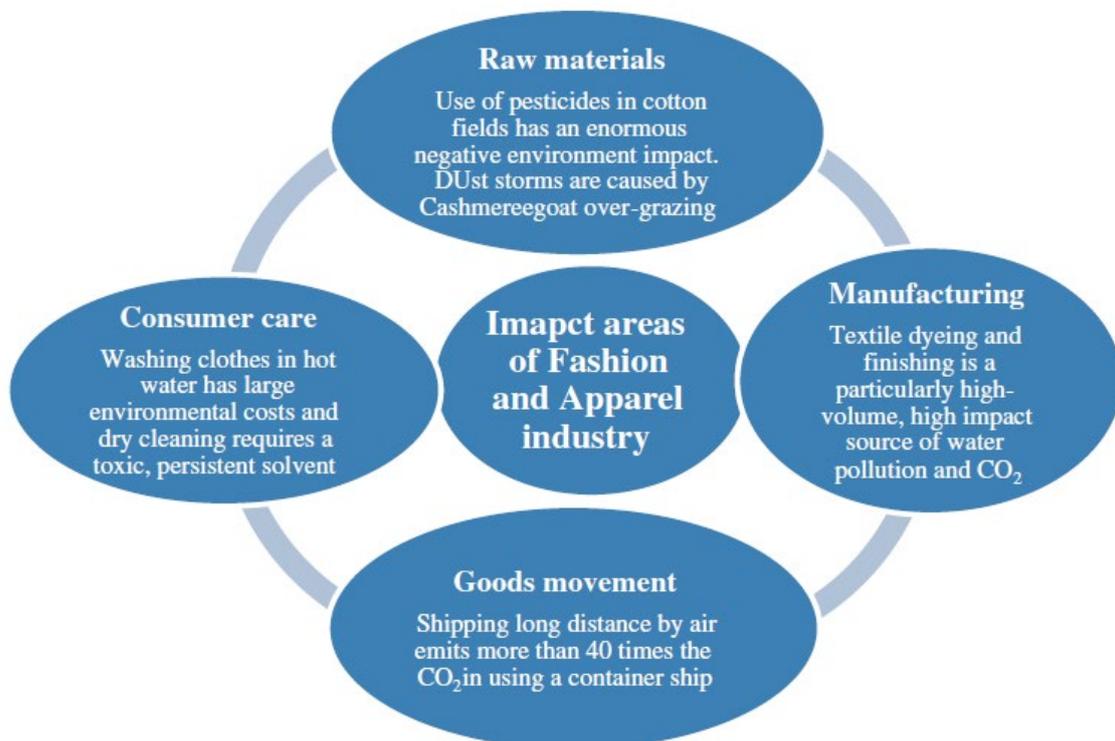


Figure 7 - Impact areas of the fashion and apparel industry

3.2.3. Transportation

The apparel industry is a global enterprise, where raw materials, manufacturers and retailers are routinely on opposite sides of the globe. Each designer and retailer must choose among container ships, railroads, trucks and airplanes to move their garments from factory to market. Each mode of transportation sends different levels of pollution into the environment and affects different populations and ecosystems around the world. However, there are many choices a retailer can make to decrease the impact of global transport and to help protect public health.

3.2.4. Consumer Care

Once purchased, the way a consumer cleans and cares for garments can have a surprisingly large impact on water and energy use. In fact, clothes frequently laundered or dry-cleaned make their biggest environmental impact once they leave the store. Washing in cold water and minimizing dry cleaning (even so-called “organic dry cleaning”) can reduce impacts substantially.

3.2.5. Environmental Impacts of Fibres

Recently, with increase in consumer interest and establishment of third party certification systems, a greater focus has been given by the textile companies to the production of sustainable fibres. New alternatives have been investigated, developed and introduced to the market. The comprehensive analyses of impact of important natural and synthetic fibres and environmental benchmark of fibres are shown in Tables 5 and 6, respectively.

<i>Textile fibre</i>	<i>Non-polluting to obtain, process and fabricate</i>	<i>Made from renewable resources</i>	<i>Fully biodegradable</i>	<i>Reusable/recyclable</i>
<i>Cotton</i>	No, Fertilizers, herbicides, pesticides, dyes and finishing chemicals used can pollute air, water, and soil.	Yes, Cotton comes from cotton plants which are renewable.	Yes	Yes, However, it is difficult to recycle cotton from postconsumer products because of the presence of dyes and other fibres.
<i>Wool</i>	No, Runoff contamination, chemicals used for cleaning, dyeing, and finishing can cause pollution.	Yes, Wool comes from sheep, which are renewable.	Yes	Yes, Wool has been recycled.
<i>Rayon</i>	No, Harsh chemicals used to process wood pulp, and dyes and finishing chemicals can cause pollution.	No, Wood pulp used for Rayon comes from mature forest.	Yes	Yes, However, rayon fibres have not been recycled
<i>Tencel</i>	No, Chemicals used for dyeing and finishing can cause pollution.	Yes, Trees used for Tencel_ are replanted.	Yes	Yes, However, Tencel_ has not been recycled.
<i>Polyester</i>	No, Chemicals used for dyeing and finishing can pollute air and water.	No, Petroleum sources are not renewable.	No	Yes, 100 % polyester has been Recycled.
<i>Nylon</i>	No, Chemicals used for dyeing and finishing can pollute air and water.	No, Petroleum sources are not renewable.	No	Yes, 100 % nylon has been Recycled.

Table 5 - impact of important natural and synthetic fibres and environmental benchmark

3.2.5.1. Cotton

Cotton is the most important apparel fiber around the world. Cotton is a natural cellulosic fiber, comes from a renewable resource, and is intrinsically biodegradable. Therefore, many consumers believe it is an environmentally responsible product. In fact, cotton plants are very prone to attack by certain insects and fungi. Cotton is the most pesticide intensive crop in the world: these pesticides injure and kill many people every year. It also takes up a large proportion of agricultural land, much of which is needed by local people to grow their own food. Herbicides, and also the chemical defoliants which are sometimes used to aid mechanical cotton harvesting, add to the toll on both the environment and human health. These chemicals typically remain in the fabric after finishing, and are released during the lifetime of the garments.

Before the fibers can be processed into textile products, the waxy outer layer on cotton must be dissolved in aqueous sodium hydroxide through a process called “scouring” so that dyes can penetrate. The same chemical is also used in the mercerization of cotton to improve performance characteristics. Furthermore, most of the cotton is bleached before dyeing or printing to yield a better coloration. Formaldehyde or related products have been used on cotton in the durable press finish to improve the wrinkle recovery of the fabrics. The carcinogenic property of formaldehyde has been a major concern with using the chemical on cotton. Despite its “natural” image, cotton production has become increasingly associated with severe negative environmental and social impacts.

Class A	Class B	Class C
<ul style="list-style-type: none"> • Recycled cotton • Mechanically recycled nylon • Mechanically recycled polyester • Recycled wool • Organic hemp • Organic linen 	<ul style="list-style-type: none"> • Tencel • Organic cotton • Chemically recycled polyester 	<ul style="list-style-type: none"> • Conventional hemp • Ramie • PLA • Conventional linen
Class D	Class E	Class F
<ul style="list-style-type: none"> • Virgin polyester • Poly-acrylic • Generic modal 	<ul style="list-style-type: none"> • Conventional cotton • Virgin nylon • Cupra • Bamboo viscose • Wool • Generic viscose 	<ul style="list-style-type: none"> • Silk • Organic wool • Leather • Spandex • Acetate • Cashmere wool • Alpaca wool • Mohair wool • Bamboo linen

Table 6 - important natural and synthetic fibres

3.2.5.2. Organic Wool

Organic wool is different from conventional wool in at least two major ways: (1) sheep cannot be dipped in insecticides to control external parasites such as ticks and lice, and (2) organic wool farmers are required to ensure that they do not exceed the natural carrying capacity of the land on which their animals graze.

The term “organic” doesn’t only cover management of the livestock according to organic or holistic management principles but also (1) processing of the raw wool, using newer, more benign processes rather than harmful scouring and descaling chemicals; and (2) wastewater treatment from scouring and processing according to Global Organic Textile Standard (GOTS).

3.2.5.3. Rayon

Rayon, the first regenerated cellulosic fiber, was produced and sold as “artificial silk” until the name “rayon” was adopted in 1924. Historically, rayon was produced by two methods: the viscose and the cuprammonium processes. The production of viscose rayon still poses a threat to the environment; the wood pulp used comes from mature forests, and the processing of wood pulp into fibre and cleaning it after extrusion uses large quantities of harsh chemicals which can contribute to water and air pollution.

3.2.5.4. Lyocell

Tencel (with the generic name lyocell) is another regenerated cellulosic fiber made from wood pulp. It was first introduced in the early 1990s and was marketed as a type of rayon without negative environmental impact. The wood pulp for Tencel comes from wood harvested from trees grown specifically for this end use. During the synthesis of the polymer, the wood pulp is dissolved in a weak bath of amine oxide, a low-toxicity and low-skin irritation solvent, and the solution is spun into a bath of diluted solvent where Tencel filaments are solidified and produced. All the solvents used in the production of Tencel filament are then recovered, purified, and recycled. In general, Tencel is biodegradable and from a renewable resource. In addition, the chemicals used in the production of Tencel fiber are significantly less hazardous to the environment.

3.2.5.5. Nylon

Nylon and polyester are among the most widely used synthetic fibers in the United States. Both fibers are produced from polymer solution obtained from the by-product of nonrenewable petroleum resources and are essentially non-biodegradable. There are concerns about the use and disposal of hazardous chemicals in the production of nylon resin solids. However, the raw material for nylon is melted in an autoclave without the use of solvents, and the polymer solution is extruded through a spinneret. The filaments are then solidified in air on cooling. After spinning, the fibers are ready to be used without cleaning or washing. However, the manufacture of nylon emits nitrous oxide, which is a substance partly responsible for depleting Earth’s ozone layer. In addition to dyes, chemicals are often added to the spinning solution to change the physical and chemical properties of the filaments before the fibers are formed. Once the fiber is formed, nylon does not require any finishing processes similar to those used on cotton or wool.

Nylon is the major fiber used in carpets, but there are problems associated with nylon carpet recycling. The problems arise from the presence of dyes or chemicals added to the polymer solution during fiber manufacturing, the wide variety of nylon polymers, and the adhesives used in nylon carpet backings. Recently, the industry has been working on recycling nylon from carpet by converting nylon fibers into caprolactam, which is used as raw material for Nylon 6.

3.2.5.6. Polyester

Polyester is the most widely used synthetic fiber and is sometimes referred to as the workhorse fiber of the industry. The production process of polyester is similar to nylon. Similar to all other synthetic fibers, polyester can be dyed at the solution stage before the fibers are formed. However, when the colors are to be added to polyester fiber products at later stages, polyester is difficult to dye. The dyeing of polyester must be achieved under pressure or in the

presence of a carrier. Some disperse dyes used on polyester have been shown to cause allergic contact dermatitis.

Unlike nylon, polyester is extensively recycled to reduce landfills. Polyester is being produced by recycling soda bottles made of polyethylene terephthalate. The other advantage of producing fibers from recycled polyester is that significantly less environmental pollution is generated compared to the production of polyester fibers made from new raw materials; it is estimated that air pollution is reduced by as much as 85 %. However, the quality of recycled polyester may not be as good as that of the virgin polyester.

3.2.5.7. Bamboo

Bamboo's eco-friendly positioning in the market has been based on the following properties:

1. A natural (that is, non-synthetic) fiber
2. A quick-growth plant (it belongs to the grass family) which sequesters greenhouse gases
3. A renewable plant which can grow back after its 3–5-year harvesting period
4. A plant which doesn't need pesticides or fertilizers during its growth phase

The manufacturing of bamboo fiber is where the debate really gets heated.

There are three methods by which bamboo may be processed into fiber for fabric production. The first is a mechanical process similar to that used to process flax or hemp; the stalks are crushed and natural enzymes break them down further, allowing fibers to be combed out. This is an expensive process but it is ecofriendly.

True bamboo fabric is known for its softness and boasts strong absorbency and anti-microbial properties, but the chemical process in bamboo rayon destroys this anti-microbial effect. Bamboo fiber can be dyed with all dyes recommended for cellulosic fibers. As usual, the dye class selection depends mainly on fastness requirements. However, as always when producing a sustainable fiber, sustainable products in pre-treatment, dyeing and finishing should also be selected.

3.2.5.8. PLA (Ingeo™)

Ingeo™ is a polylactide acid fiber (PLA fiber) made from 100 % annually renewable resources and was introduced by Cargill Dow LLC to the textile market in January 2003. The name Ingeo literally means "ingredients from the Earth". Ingeo™ is produced by fermentation of dextrose obtained in this case from corn starch. Other potential feedstocks could be rice and potatoes and even grass or straw. The fermentation products are subsequently transformed by condensation and vacuum extraction into a high-performance polymer called polylactic acid from which the branded Ingeo fibers and filament yarns are extruded.

Ingeo combines the comfort properties of natural fibres with the performance of man-made fibers such as breathability, moisture management, crease resistance, no support of bacterial growth, inherent flame retardancy and UV resistance. In addition, the fibers have environmental benefits resulting from using renewable resources as their feedstock, including reduced CO₂ emissions and less fossil fuel usage than other materials (estimated at up to 50 %). In textile applications Ingeo is used for fiber fill, knitted apparel, furnishings, carpets and denim.

3.2.5.9. Recycled PET

Two kinds of recycled PET are available on the market. One is mechanically recycled PET (only melting of PET) which has a strong yellowish shade and is not suitable for white or pale shades. To get a better degree of whiteness, a bleaching process has to be carried out, and even then

the OBA has to be tinted with some dyes to get close to the required level of white. The bleaching process is not ecofriendly at all and adds additional cost to the process. This kind of recycled PET should only be used for dark shades (mainly navy + black). The other type of recycled PET is a full chemically recycled PET. This has a similar shade to “virgin PET” and can be used without any problems for all shades. It is claimed that the cost of recycled PET can be twice the cost of virgin PET.

Regarding dyeing, both recycled PETs behave the same as “virgin PET” but careful dye selection is necessary to ensure the highest levels of exhaustion compatibility and fastness. As part of its confidence program, DyStar has recently launched a range of “green” Dianix dyes which are ideally suited for the processing of recycled PET. A comprehensive screening program covering raw materials and intermediates as well as sophisticated dye manufacturing controls ensures that no harmful chemicals are carried through onto the fiber.

3.2.6. Environmental Impact of Textile Processes

It is a fact that the textile industry has grown many times during the last decades to meet global and domestic demand. This tremendous growth has also led to a parallel growth in environmental problems, which remained unnoticed. Any industrial activity produces pollution in one form or the other, and the textile industry certainly released a wide spectrum of pollution into the environment. The textile manufacturing process is characterized by the high consumption of resources such as water, fuel and a variety of chemicals in a long process sequence which generates a significant amount of waste.

The common practices of low process efficiency result in substantial wastage of resources and severe damage to the environment. The practice of age-old processes ranging from raw material input to final products compounded major environmental impact. As well as the old techniques, the chemicals used, unskilled labor, logistics employed, untreated effluent disposal, erroneous working methods and improper sanitation are generating wastewater, noise, dust, toxic waste, gaseous waste, hazardous chemicals and heaps of solid waste.

The main environmental problems associated with the textile industry are typically those associated with water body pollution caused by discharge of untreated effluents. Other environmental issues of equal importance are air emission, notably volatile organic compounds (VOCs) and excessive noise or odor as well as workspace safety. An overview of the amounts of waste generated within textile processes is presented in Table 7.

3.2.7. Environmental Impact of Spinning

During spinning, fibres are subjected to various mechanical processes which comb, align and spin them to produce a yarn. In some cases two or more yarns are then twisted together to form a twine. Chemical auxiliaries are used to provide lubrication, allowing high speed processing. Traditionally mineral oils were used, a source of poly aromatic hydrocarbons (PAHs). PAHs are prevalent pollutants in both terrestrial and aquatic environments which can cause a wide range of toxic effects; some are known human carcinogens. Today they have been largely replaced by synthetic oils (silicone oils, polyglycols) and ester oils. These offer better performance and have more uniform properties. As the oils are applied as aqueous preparations and are not generally water soluble, emulsifiers are required. Generally these are non-ionic surfactants such as alcohol ethoxylates and alkylphenol ethoxylates. The aqueous preparations must be protected from degradation during storage so preservatives such as bactericides and fungicides are also added. As discussed later, these end up in finishing plant effluent streams.

Process	Emission	Waste water	Solid wastes
<i>Fibre preparation</i>	Little or none	Little or none	Fibre waste and packaging waste
<i>Yarn spinning</i>	Little or none	Little or none	Packaging wastes; sized yarn; fibre waste;
<i>Slashing/sizing</i>	VOCs	BOD: COD, metals	Fibre lint; yarn waste; packaging waste;
<i>Weaving</i>	Little or none	Little or none	cleaning waste, size unused starch-based sized
<i>Knitting</i>	Little or none	Little or none	Packaging waste; yarn and fabric scraps; off-
<i>Tufting</i>	Little or none	Little or none	spec fabric; used oil.
<i>Desizing</i>	VOCs from glycol ethers	BOD from sizes lubricants;	Packaging waste yarn and fabric scraps; off-
<i>Scouring</i>	VOCs from glycol ethers and	biocides; anti-static	spec fabric
<i>Bleaching</i>	Little or none	compounds	Packaging waste yarn, fabric scraps; offspec
<i>Singeing</i>	Small amounts of exhaust gases	Disinfectants, insecticide	fabric
<i>Mercerising</i>	from the burners	residues; NaOH; detergents,	Packaging waste; fibre lint; yarn waste;
<i>Heat-setting</i>	Little or none	oils; knitting lubricants;	cleaning and maintenance materials
<i>Dyeing</i>	Volatilization of spin finish	spin finishes; spent solvents	Little or none
<i>Printing</i>	agents synthetic fibre	H ₂ O ₂ , stabilizers; high pH	Little or none; even if little, the impact could be
<i>Finishing</i>	manufacture	Little or none	considerable
	VOCs	High pH; NaOH	Little or none
		Little or none	Little or none
		Metals; salt; surfactants;	Little or none
		organic processing	Little or none
		assistants; cationic	Little or none
		materials; colour; BOD;	Little or none
		COD; sulfide;	Little or none
		acidity/alkalinity; spent	Little or none
		solvents	Little or none
		Suspended solids; urea;	Little or none
	Solvents, acetic acid drying and	solvents; colour; metals;	Little or none
	curing oven emissions	heat; BOD; foam	Little or none
	combustion; gases	COD; suspended solids;	Little or none
	VOCs; contaminants in	toxic materials; spot	Little or none
	purchased	solvents	Little or none
	chemicals; formaldehyde		Little or none
	vapors; combustion gases		Little or none

Table 7 - Wastes generated during textile manufacturing

Synthetic oils do not contain the same levels of impurities (no metals, etc.) as mineral oils and some biodegrade. Ester oils are also biodegradable and easier to emulsify than mineral oils (therefore a lower surfactant loading is required). For the spinning of synthetic fibres, silicon oils predominate and account for up to 7 % of the yarn by weight. Though these are non-toxic and bio-eliminable, emulsification is difficult and so large amounts of surfactant are employed (38).

3.3. Waste Generation in Apparel Industry

3.3.1. Types of Wastes

In textile and apparel industries, there are different types of wastes are obtained and they are classified as three types namely: (39)

- i. Production waste
- ii. Pre-consumer waste and
- iii. Post-consumer waste

Production waste — These are all the leftover items in the apparel manufacturing firm such as trimmings, proofs, leftover fabric, off-cuts, ends of rolls, etc. Production wastes are one of the important waste types due to its virginity and also used for many reuse, recycle and up cycling process. This is mainly because of the volume produced is generally quite large and regular.

Pre-consumer waste— It is a material that was discarded before it was ready for consumer use. Competition for the biweekly changing collections becomes the basis of most of pre consumer waste generation in the apparel industry.

Post-consumer waste—This types of waste consists any type of apparels or home textiles that an individual does not require anymore and chooses to dispose of due to different reasons like, worn out conditions or outgrown or out of fashion or etc.,

These kind of materials are normally of good quality, that can be recuperated and along these lines reused by another individual as second-hand garments a lot of which is sold to underdeveloped countries.

3.3.2. Waste Management Methods

The general waste management concept is 4 Rs.—reduce, reuse, recycle and recover. This concept decides the methods according to their desirability. This waste management concept insists, waste generation should be prevented or reduced to the possible extent as a first step. On the off chance that at all it is created, the waste ought to be reused in view of their probability. If not or after reuse, the waste can be recycled based on the material. Finally, if it is possible, the recovery options also can be tried to recover its raw material. In apparel industry, the purpose of the waste management system is to separate the most extreme practical benefits from garments while at the same time creating the base measure of waste and causing the minimum environmental impact.

Reduce—Meaning in general as less buying and using less amount of product in all possible way. The concept of zero waste in apparel and fashion industries is not a new concept. However, due to business motivations and other requirements the zero waste concepts were not implemented even at the possible situation. The kind of production, with no waste can be classified under reduce strategy. (40)

Reuse—It is an important strategy for apparel industry. It focuses on the reuse of rejected material, re-distribution and resale of rejected apparel product. In the case of apparel manufacturing industry, the reuse concept advises to utilize the waste fabric or material into a value added item for another product.

Recycle—is the process to change items considered as waste into new products to prevent waste of potentially useful materials and reduce the consumption of fresh raw materials. Most of the time energy and water is used to change the physical properties of the waste material. Hence, it is recommended to go for reuse and reduce strategy.

Recycle is concerned with providing the manufacturer with re-processed raw material to use as an input to make new goods. Recycling material saves resources and usual uses less energy

than the production of new material. The recycling process can be performed into two ways namely as discussed in the following sections.

1. **Up-cycling**—It is the way toward changing over old or discarded materials into something valuable and often beautiful. While doing up-cycle, the process creates a new purpose to the old item. The objective of up-cycling is to avoid squandering possibly useful materials by making utilization of existing ones. This decreases the utilization of new raw materials while making new items.

2. **Down-cycling**—A procedure of changing over important items into low-value raw materials. Contrasted with the up-cycling procedure, this one is least preferred. For instance: making recycled papers from paper, making rags from used cloths and apparels. Despite the fact that down-cycling helps the planet since it keeps things out of landfills (for a period at any rate) commonly it will in the long run wind up there.

3.3.3. Fabric Wastes in Various Part of Apparel Industry

In apparel industry, the initial process starts in the fabric department, where the manufacturing plant receives raw material from the supplier. This first point of waste generation is the fabric inspection. After inspection, the fabric is laid on the cutting table and cutting was carried out by cutting masters. It is the second point of waste generation in the department. After cutting process, the cut parts were numbered sequentially to avoid shade variation during the sewing process. After numbering and bundling process all the cut part components were transferred to sewing line for sewing process. This is the third point of waste generation. During sewing process, either due to sewing quality issues or cutting issues the components uses to get rejected. After sewing the garments were passes to end line quality auditing department, where the quality checkers will perform 100% end line checking, here if any unrepairable defects found the garments will be rejected. This is another point of garment rejection. After this the garments will be packed and sent for dispatch. The following Figure 8 represents the process sequence and Waste generation points in the apparel production process. (39)

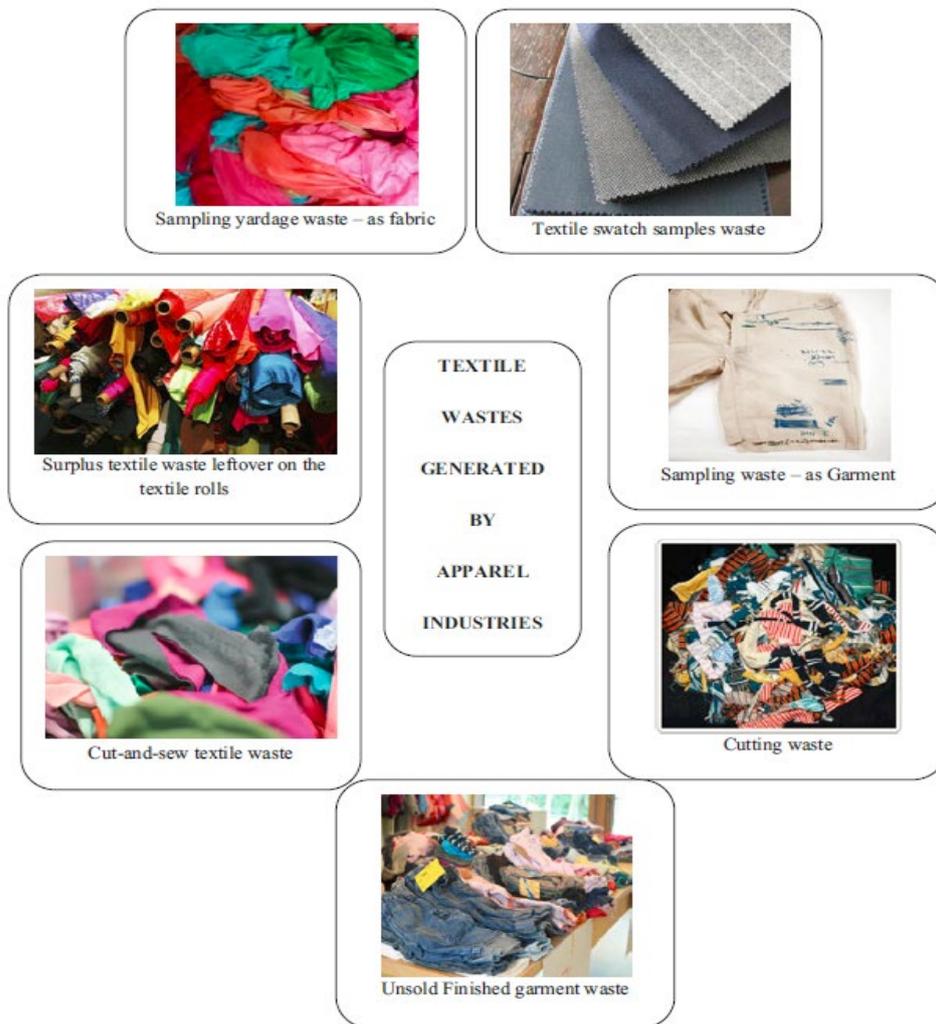


Figure 8 - different types of wastes generated in the apparel industry

Figure 8 shows details the different types of wastes generated in the apparel industry from the sample making process to the retail shop. They are details as follows.

1. Sampling waste as Garment and Fabric yardage

In sampling department, during the garment development stages, different types of the fabrics will be sourced and utilized for the sample development. After development, the garments and fabrics will be sent to the buyer for the approval and based on the comments, the sampled or fabrics may be accepted and rejected.

In spite of the acceptance, the buyer may also want to revise the style feature or incorporate few changes in the design. In that stage that samples and fabrics are thrown out as a waste at the least case.

2. Cutting department waste

The first waste developed by cutting department is cut waste, which was discussed in detail in the following section. The second one is left over fabric after the required consumption. This leftover fabric to the maximum extent will be utilized and very short and unused material will be discarded as waste in this stage.

3. Cut and sew waste

This is the waste that generally coming out of sewing defect and quality issue. This waste are sometimes fully made garments or sometimes semi-finished garment.

4. Unsold finished garment

It is another area, after the completion of the particular season, the manufacturer or the brand will come up with new set of styles according to the current trend and the old style will be removed from the retail outlet. Most of the time these items will be sold as a second hand product or for the discounted prices. However, few brands because of their brand image they will shred or discard the old cloths as a waste. (39)

A Case Study in Apparel Industry

As a preliminary work, the previous researches on the apparel industry wastes were analyzed. There are very few studies are available in this area. A study by Rahman and Haque showed the different waste percentage of the cutting department of an apparel industry. They have studied the waste fabric production in the cutting, panel checking process, sewing and finishing process. The researchers conducted a study on five different knit T shirt manufacturing apparel unit in Bangladesh and the average waste percentage calculated department wise in those industry. In their study they have mentioned that out of the selected fabric quantity, in and average a 26.52% of fabric goes as a waste in the overall garment manufacturing process. They have also mentioned that out of that 26.52%, a maximum of 13.57% of waste generated in the cutting section. The average wastes generated at the end of each department activity are provided in the Table 8. (41)

Day	Fabric weight taken in gr	Fabric Waste %				Total Waste %
		Cutting	Panel Checking	Sewing	Finishing	
1	16,551	16.50	6.67	4.15	1.66	28.98
2	25,255	15.04	6.78	4.24	1.69	27.75
3	27,541	13.83	6.90	4.29	1.72	26.74
4	27,798	10.96	7.12	4.45	1.78	24.31
5	29,717	11.56	7.09	4.42	1.76	24.83
Average	25,372	13.57	6.91	4.31	1.72	26.52

Table 8 - Percentage waste in different sections of apparel industry

In another study performed by Tanvir and Mahmood, they have analysed the knit garment manufacturing industries in the Bangladesh. They have measured the waste generation quantity in each point of the apparel industry for different order. They have collected the data from 25 industries all over the Bangladesh. As a finding they have listed the following Table 2 in their result. From the study conducted in the 25 apparel industry, researchers collected the waste percentage in the four points namely, inspection loss, cutting loss, sewing loss and finishing loss. From the study they had concluded that around 25% of the fabrics loss happening in the process. Their results also indicated that, out of all the selected industries, the waste percentage was noted higher in fabric inspection and fabric cutting activity. The waste generation the cutting section is significantly higher than that of other departments of the apparel unit. In this study it can be seen that out of the selected fabric quantity of 136,930 kg, the maximum of 2910 kg of fabric wasted in the cutting section alone. Based on the available literature, it can be clearly seen that, the major part of the waste from the industry is from cutting department. While considering the waste from the sewing and finishing department, the cutting department wastes are significantly high. In view of these research, the cutting waste percentage of the Tirupur knit apparel industries were collected to understand the approximate contribution percentage. The results of the survey are provided in the Table 9.

Order No	Gram per square meter of the fabric	Fabric input qty in kg	Fabric waste qty in kg	Waste %
1	155	850	59	7
2	155	1206	237	19
3	175	1885	482	20
4	155	2000	415	20
5	184	1278	464	27
6	175	1666	401	19
7	208	2207	591	21
8	160	1260	340	27
9	180	1010	240	24
10	200	1450	648	44
11	155	1850	385	21
12	170	2250	462	20
13	180	1885	420	22
14	180	2020	382	19
15	175	1550	216	14
Average		2437	5745	
Average waste %		24%		

Table 9 - Cutting department waste calculation

From the result it can be seen that for 15 different orders from 10 various factories, the average waste percentage is noted as 23.57% in cutting department alone. These results are in line with the studies of the pervious researchers Tanvir & Mahmood (2014) and Rahman&Haque (2016). Another important factor observed during the study is, the factories where we collected the cutting waste uses computerized marker plan. It can be seen that, the influence of garment style and style requirement plays a vital role in the fabric waste irrespective of the methods used formarker planning. Particularly in some style, example order number 10, in the Table 9, represents a style which wastes around 44.6% of the fabric only due to style requirements. (41)

3.4. Textile Recycling and Reuse

Recycling implies the breakdown of a thing into its unrefined materials with the end goal that the rough material can be recuperated and used as a piece of new items. On the other hand, recycle insinuates a present thing being used again inside a comparable creation chain. Textile material recycling is the strategy by which old pieces of clothing and diverse materials are recovered for recycle or material recovery.

It is the explanation behind the material recycling industry. Material recycling may incorporate recouping pre-consumer waste or post-consumer misuse (Figure 9). There are different ways to deal with perceive the sorts of recycling possible inside the material and dress sets. (42)

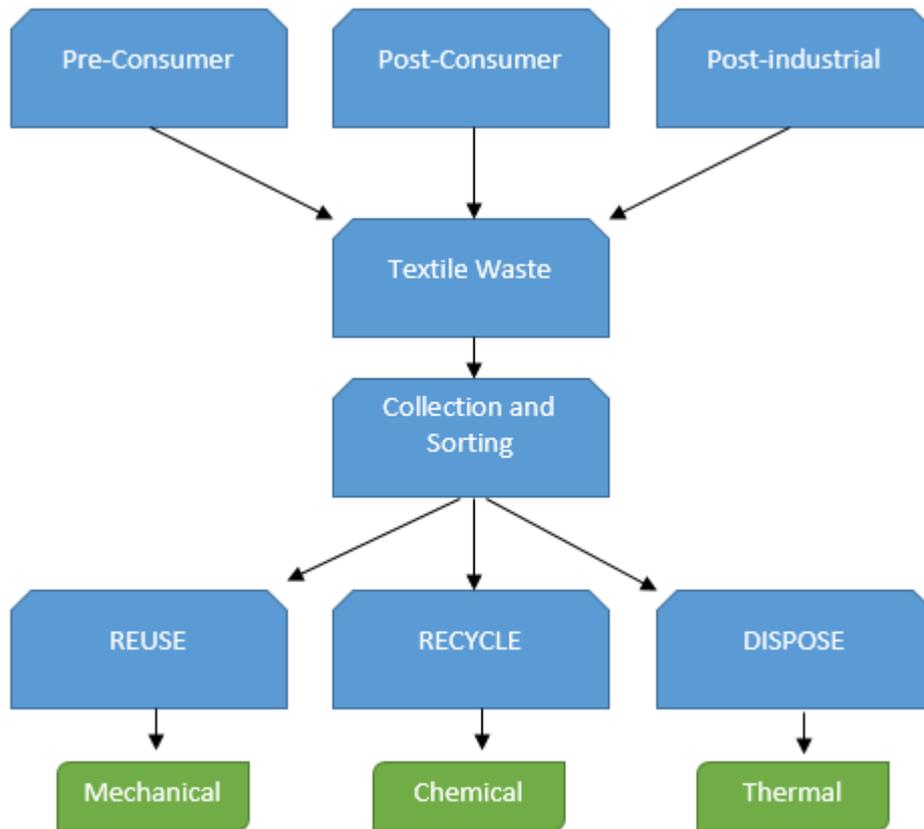


Figure 9 - Types of textile waste and recycling process

Textile material recycling impacts numerous substances and contributes fundamentally to the social obligation of the present society. By recycling, organizations can understand bigger benefits since they stay away from accuses related of dumping in landfills; in the meantime, material recycling adds to positive attitude related with environmentalism, work for hardly employable workers, commitments to philanthropies and debacle help, and the development of utilized attire to regions of the world where modest garments is required. Since materials are almost 100% recyclable, nothing in the material and attire industry ought to be squandered. Fiber utilization development is a twofold edged sword in that while expanded fiber utilization stimulates the economy, it likewise contributes altogether to the issue of transfer. As shoppers keep on buying at a rate that meets needs as opposed to needs, the issue of what to do with squander is intensified. Material waste is made out of both common and engineered materials, for example, cotton, fleece, polyester, nylon and elastane. After engineered filaments went onto the market in the mid twentieth century, material recycling turned out to be more intricate for two unmistakable reasons: (1) expanded fiber quality made it harder to shred or “open” the fibers, and (2) fiber mixes made it harder to purge the arranging procedure.

The procedure of material recycling happens when post mechanical or post-consumer squander enters the recycling pipeline through assembling waste accumulation or passing on to someone else for reuse. (42).

3.4.1. Types of Waste from Textile Industry

The waste created from material industry can be grouped into two uses as:

- Pre-consumer waste

- Post-consumer waste

3.4.1.1. Pre-consumer Waste

Pre-consumer waste is a material that was disposed of before it was prepared for customer utilize. Pre-consumer recycled materials can be separated and revamped into comparative or diverse materials, or can be sold as such to outsider purchasers who at that point utilize those materials for buyer items.

Pre-consumer material waste for the most part alludes to squander results from fiber, yarn, material, and clothing fabricating. It can be process closes, scraps, clippings, or merchandise harmed amid creation, and most is recovered and recycled as crude materials for the car, furniture, sleeping cushion, coarse yarn, home outfitting, paper, and different ventures. Pre-consumer squanders are produced all through the first phases of the inventory network.

In the crude materials area (fiber and yarn creation), ginning squanders, opening squanders, checking squanders, comber noils, brushed waste yarns, meandering squanders, ring turning waste fibers, ring-spun squander yarns, open-end spinning waste fibers, and open-end spinning yarn squanders are usually gathered for recycling.

3.4.1.2. Postconsumer Waste

Postconsumer material waste for the most part alludes to any item that the individual does not require anymore and chooses to dispose of because of wear or harm and regularly incorporates utilized or worn apparel, bed cloths, towels, and other buyer materials. Postconsumer squander which can be recuperated are dress, wraps/window ornaments, towels, sheets and covers, clean clothes and sewing leftovers, table materials belts totes matched shoes and socks. Post-consumer waste is brought from general society, which incorporates things that have no more use for the proprietor.

3.4.2. Significance of Fiber Recycling

There are a few drawbacks related with the present land filling of textile fibrous waste. Initially, a tipping charge is required. Second, because of ecological concerns, there is expanding interest to forbid polymers from landfills. Third, land filling polymers is a misuse of vitality and materials. Assortments of advances have been created because of client requests for recycled products and as contrasting options to land filling. Aside from the instance of direct reuse, which is a typical type of usage for disposed of materials, some preparing is included to change over the waste into an item.

As the textile, attire and retail businesses move to wind up noticeably more practical, a region of intrigue is the utilization of recycled fiber, yarn, texture, and item content in the advancement and generation of new items. The choice to utilize reused materials in items must happen during plan and item improvement and proceed all through assembling forms.

There are two phases in reusing—gathering and handling.

Recycled products utilized as a part of material and clothing items can be acquired all through the material and attire store network and post-consumer accumulation techniques. The utilization of recycled crude materials lines up with the bigger developments of worldwide ventures toward a circular economy and closed loop generation.

Textile material recycling is for both, natural and financial advantages. It maintains a strategic distance from many contaminating and vitality serious procedures that are utilized to make materials from crisp materials.

3.4.3. Characteristics of Recycled Fibers

Recycled fibers are appropriate to making nonwoven and yarns. When compared with initial primary fibers, recycled fibers demonstrate diverse qualities. The harm they endure at the time of production involves a wide range of fiber lengths with a high offer in short fibers and in addition strings and bits of texture not separated.

Characteristics of recycled fibers are impacted by the loss being referred to, its pretreatment and the separating procedure all things being considered. Usually, recycled fibers are accessible as mixes. Similarly as with the preparing of recycled fibers into yarns, nonwovens require extents of separated filaments to be as high as could be expected under the circumstances. Their lengths ought to be adequate to experience the spinning or web development process being referred to. Fragments of yarn or string still contained in the mix of recycled fibers directly add to lattice development in the nonwoven or they are additionally separated into filaments during the checking procedure. Recycled fibers are promoted at low value, essential fiber materials made of regular or engineered substances, adding to holding costs down. When compared with initial primary fibers, the nature of recycled filaments is difficult to characterize.

3.4.4. Recycling Process

Recycling is the breakdown of an item into its crude materials. For quite a long time, textile products such as fabrics and garments were separated to the yarn arrange and the yarn was utilized to deliver distinctive weaved or woven textures. Now and again, the yarns are additionally separated to the fiber stage and afterward the fibers were respun into yarns to be utilized as a part of new material items. Inclinations for recycling of material squanders in the business appear to the overwhelmingly thermoplastic polymer-based fibers because of the ease and plausibility of reprocessing them. Besides, these materials can go up against various structures and shapes sub-sequent to recycling. Regular natural fibers, for example, cotton, fleece, and silk are likewise finding their routes into recycling streams. The two essential stages engaged with recycling are gathering and reprocessing.

With respect to textile materials and attire industry, the accumulation procedure happens at different focuses through the inventory network, and there are programs where the general population can be associated with the procedure. Squander is additionally gathered from sources outside the material and clothing industry for reprocessing and use in attire and material finished results. Reprocessing of the gathered materials is basic in deciding if it will add to an open-or closed circle framework. There are various explanations behind barring material from the circle. Two basic purposes behind this prohibition are:

- (1) debasement of the crude material that outcome in decreased quality and
- (2) consolidation of the crude material into an item that is not recyclable.

3.4.4.1. Open-Loop Recycling (OLR)

Open-loop recycling alludes to a framework in which an item's crude material is separated to be utilized as a part of a moment, frequently random item framework. For the most part, the second item won't be recycled and rather be discarded toward the finish of its life. In any case,

OLR ordinarily just postpones a material’s definitive entry to municipal solid waste, as there are cut-off points to how regularly a material can be recycled without quality being corrupted (Figure 10). Ordinarily, OLR recycled things in textile and attire incorporate (43)

1. Pre-consumer textile material waste, for example, offcuts from the cutting procedure;
2. Post-consumer material waste as entire pieces of clothing; and
3. Post-consumer PET containers that might be fabricated into recycled PET (RPET) fiber.

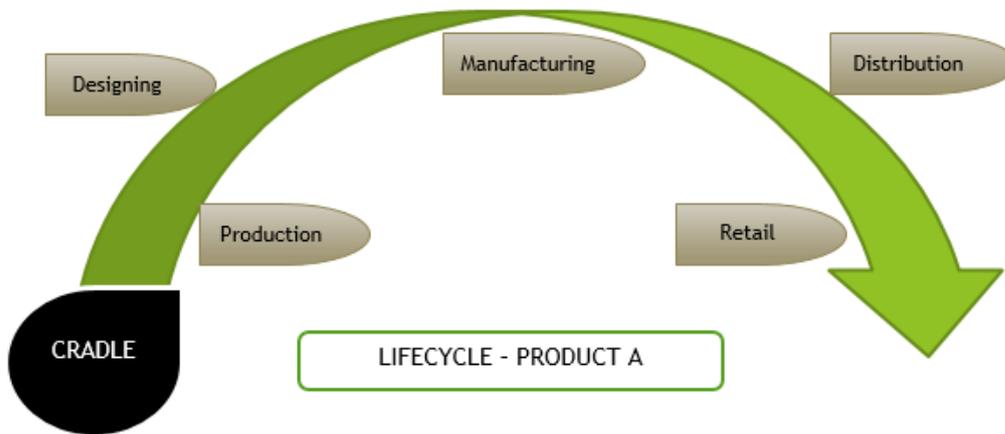


Figure 10 - Open-loop recycling A

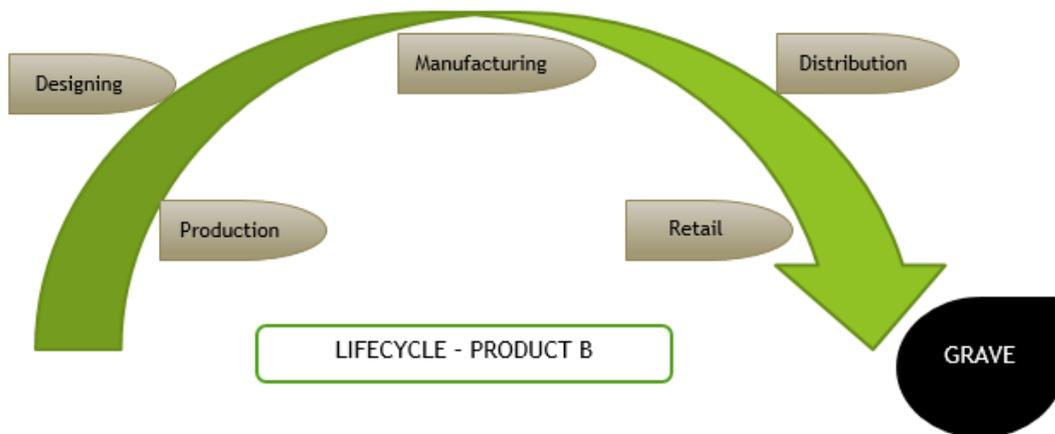


Figure 11 - Open-loop recycling B

OLR has demonstrated achievable in the fashion setting, both in accumulation of pre-and post-consumer material waste for use in different items, and in gathering of utilized jugs or bottles for recycling into materials. As of now, OLR of PET bottles or jugs to fiber has had the best accomplishment for recycle as a material in the textile and fashion area, with an open circle of waste from the first item (PET jugs) utilized as feedstock for the second item framework (polyester texture to piece of clothing).

A typical approach is to mix the recycled yarns with virgin fibers to make materials that are of clothing quality.

Conversion of PET bottle to fiber using OLR

PET bottles or jugs to fiber is an OLR strategy in which PET containers are recycled into PET flakes, re-spun into fiber and afterward woven or sewed into materials. As PET is non-

biodegradable, recycling is a proper utilization of the asset. PET containers have been recycled since the 1970s.

The procedure for mechanically recycling PET jugs to fiber is as per the following:

1. Containers are gathered, cleaned and arranged by shading.
2. Marks are expelled.
3. Bottles or Jugs are handled into PET flakes.
4. The PET flakes are liquefied and expelled through the spinneret into new fibers. The nature and quality of RPET in mechanical preparing is for the most part not high when contrasted with virgin PET as virtue depends intensely on polluting influences or contaminants inside the containers. And additionally the mechanical procedure, PET can be recycled utilizing a substance procedure. Stages 1 to 3 are indistinguishable to the above; the PET flakes are chemically changed and come back to an oligomer or monomer.

3.4.4.2. Closed-Loop Recycling (CLR)

CLR alludes to recycling techniques whereby the material being recycled is a similar material being delivered: 'an item enters the generation chain of a similar item again after utilize'. The waste material or fiber re-enters a piece of clothing generation chain, both pre-and post-consumer mechanically recycled materials might be viewed as closed-loop recycled. Successful CLR has demonstrated more troublesome at scale than OLR. Figure 12 represents the closed-loop lifecycle of textile material. (43)

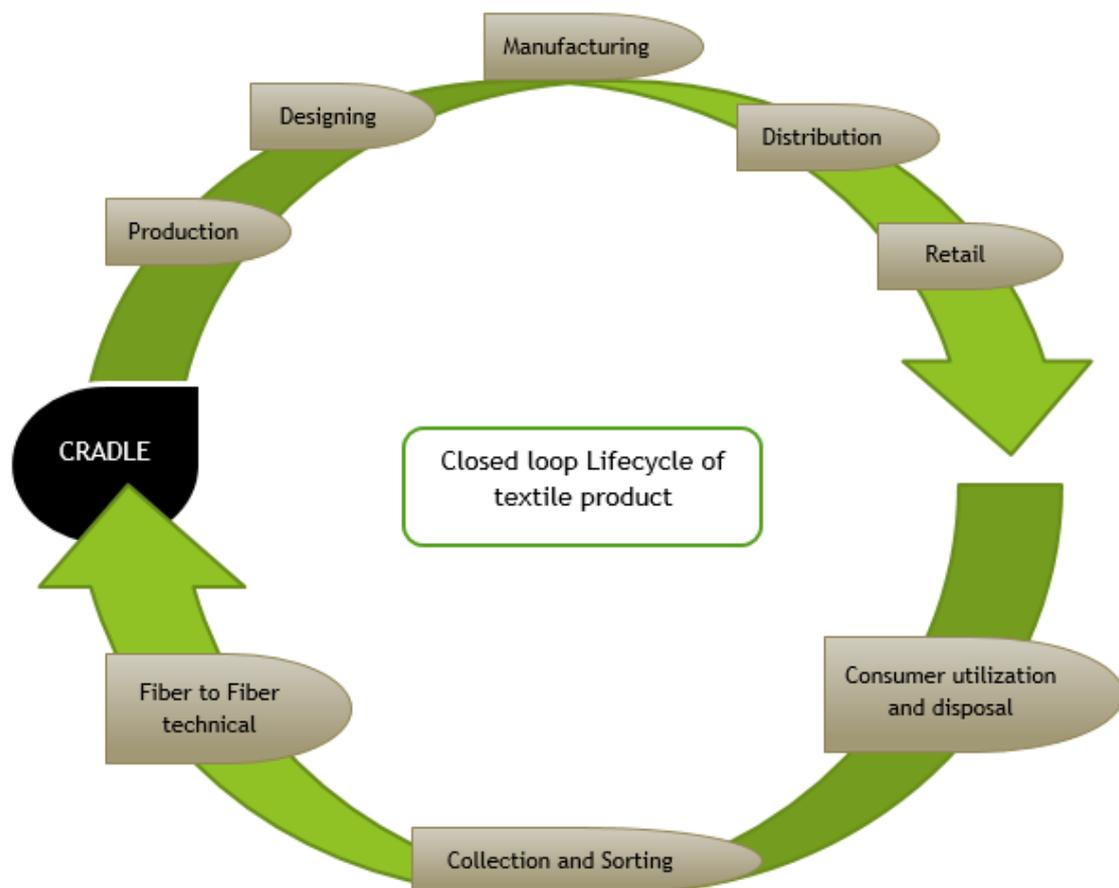


Figure 12 - Closed-loop recycling

Support to-support CLR (Cradle-to-cradle)

The support-to-support philosophy is a radical way to deal with CLR in which a CLR fiber will be recyclable and also reused into a similar creation chain. C2C closed-loop framework, squander is recovered and utilized again in the generation of results of the same or higher esteem. Squander is redirected into either organic or specialized streams. Organic waste can be treated with the soil, while specialized waste can be recycled inside industry to make similar items once more. A related closed loop approach is in the recycle of articles of clothing. Both recycling of garments and furthermore upcycling of apparel are identified with CLR. Closed-loop reuse suggests apparel can have different valuable lives on the second-hand showcase. In spite of the fact that recycle of articles of clothing isn't recycling in the feeling of separating an item into its crude materials, it compares to CLR in that the item may enter another life cycle inside a similar generation chain. (44)

3.4.5. Textile Recycling Approaches

In the clothing industry, primary or essential recycling is the social event of pre-consumer offcuts of the surface from creation. Cut-and-sew manufacture of dress infers that there is basic material waste happening on account of the additional surface of solitary pattern material.

Secondary or Auxiliary recycling incorporates aggregation and reusing of postconsumer material misuses, for instance, pieces of clothing, materials identified with families, and so forth. Dependent upon consumer action, this clothing may be sent to civil strong waste or provided for philanthropies or social event organizations. Garments gathering association will then sort the dress into higher quality articles of clothing proper for resale and lower quality clothing sensible for recycling. (42)

S. No	Stages	Process
1	Primary	Recycling materials from industries
2	Secondary	Conversion of post-consumer product into useful material
3	Tertiary	Conversion of plastic wastes into fuels
4	Quaternary	Burning wastes for fixing energy

Table 10 - Stages in textile recycling

Tertiary reusing incorporates the engineered or chemical degradation of nylon or polyethylene terephthalate (PET) for re-polymerization. This requires either spotless, organized pre-consumer waste or post-consumer misuse, orchestrated by nature of fiber, as a feedstock.

Quaternary reusing insinuates devouring the fibrous solid strong waste and utilizing the heat vitality delivered. In quaternary reusing, the embedded essentialness can be recuperated through consuming procedure or burning. Overall recycling stages and its process is represented in Table 10.

3.5. Methods of Recycling Fibers

3.5.1. Mechanical Recycling

Mechanical recycling procedures can bring about the creation of texture, yarns, or fibers to be utilized as a part of new textile products. The disposed of material is opened up, clothing is dismantled, and textures are cut into little pieces. It is then gone through a spinning drum to proceed with the breakdown and fibers are acquired. This procedure is known as garneting. The subsequent fiber attributes of length, fineness, quality, polymer, and shading decide the quality and what the most suitable new final result would be. Ordinarily, squander gathered from the assembling store network will create higher-quality recycled fibers that those gathered from post-consumer squander. The pre-consumer and post-industrial handled waste can be respun into yarns which woven or weaved into textures, and after that utilized as a part of attire, sheeting, and upholstery. Mid-range review fibers can be utilized to make textures however are utilized as a part of final results, for example, wipes and fillings. Lower quality

fibers will be utilized as fortification in different structures (i.e., concrete), nonwoven textures, cover underlay, shoe decorates, car sound and warm protection, home protection, stuffing for toys, and opposite final results. Plastics, including plastic containers and thermoplastic fibers, are generally recycled utilizing mechanical strategies. In these cases, the plastic waste is cleaved into little flakes that are liquefied and after that expelled into a shape to be utilized as a part of another item. This liquefy can be expelled into filaments, yarns, or other framed items. There is a little discernible contrast between virgin polyester and recycled polyester fibers. This is a typical strategy for reprocessing the plastic water bottles and fishing nets. In any case, not all recycled thermoplastic fibers have properties like virgin fibers (Hawley 2006). The outline of mechanical recycling process is given in Figure 14. (44)

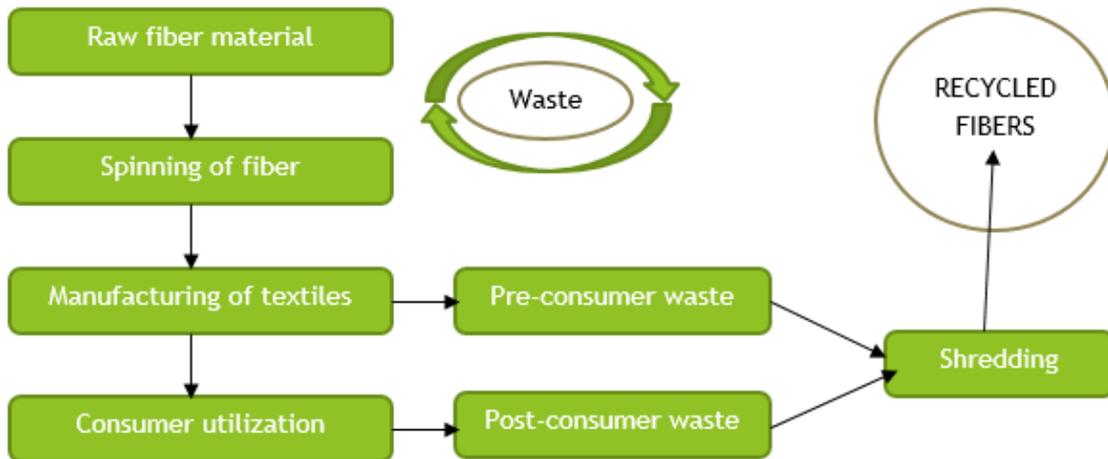


Figure 13 - Mechanical recycling of fibers

3.5.2. Chemical Recycling

Chemical recycling is the other technique regularly used to process the gathered waste in the material business. Manufactured fibers including polyesters, polyamides, and polyolefins can be artificially reused. This falls under the tertiary class of recycling which requires the separating of the manufactured fibers for re-polymerization. This procedure can be utilized when PET plastic water bottles are reused. Regardless of whether it is the accumulation of utilized polyester attire, texture scraps, yarns squander, or different plastics, the recycled things are broken into little pieces from which chips are delivered. The steps involved in chemical recycling are presented in Fig. 14. The chips are deteriorated to frame dimethyl terephthalate, which is then re-polymerized and spun into new polyester fibers, filaments, and yarns. Mixes are specifically testing to recycle due to the different physical and chemical properties of the fibers in the waste. Cotton and polyester mixes are a standout amongst the most regularly utilized attire and home material things. Chemical recycling has demonstrated effective when utilized with mixed materials as it utilizes a specific corruption strategy. In results of cotton and polyester, the fibers can be artificially isolated and afterward transformed into new fibers. Right now, there is a procedure being created utilizing n-methyl morpholine-N-Oxide, which breaks down cellulose. The broke up cellulose and polyester are isolated by filtration and the caught polyester is respun into a fiber, filament, or yarn. The broke down cellulose can be utilized as a part of the generation of recovered cellulosic fibers including Lyocell. Nylon and spandex is a mix usually found in superior sportswear and dynamic wear. Usually, the level of nylon is considerably more noteworthy than that of spandex and nylon can be recycled and reused. It is realized that spandex can be expelled from mixed textures by dissolving it in solvents, for example, N,N-dimethyl formamide. Nevertheless, this dissolvable is costly and there are environmental issues with its utilization. There has been accomplishment by first treating the mixed texture with warmth to corrupt the spandex, and

after that presenting the texture to a washing procedure utilizing ethanol, which successfully evacuates the spandex deposit leaving just the nylon.

Today, for results of single fiber content textures, mechanical recycling is more noticeable. The substance recycling systems require more vitality utilization and there is high capital speculation so this choice is common for substantial scale producers.

As the innovation enhances, the interest for recycled content increments and as the cost of virgin crude materials increments, there is probably going to be a move from mechanical to chemical recycling of these materials. (45)

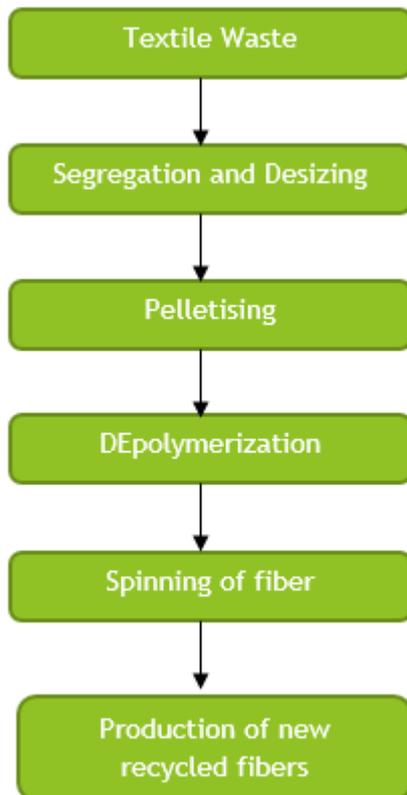


Figure 14 - Chemical recycling of fibers

3.5.3. Applications of Recycled Fibers

Recycled fibers can be made from a diversity of textile waste. Both quality and process capacities of such fibers rely upon the sort of waste. Conventional are the pure arranged fibers of astounding which are accomplished from spinning fiber waste. Interestingly, recycled fibers produced using end-of-life materials are of considerably poorer quality. They will seldom be found of homogenous fiber compose. There are numerous routes open to utilizing recycled fibers in both textile material and non-textile material items. The acceptability of procedures relies upon squander attributes and on the amount they cost.

3.5.3.1. Yarns

The waste created in a textile plant is a vital factor in deciding the working expense and in this way in affecting mill benefits. The recovered fibers from waste can be utilized to deliver mixed yarns in various parts. These fibers can be reused for the open end spinning and contact spinning however present process endeavors on ring spinning are likewise in advance. Results

likewise showed that the recovered fibers have a decent clean capacity which permits its mix with virgin filaments. This yarn can be woven or weaved for some uncommon reason yet till a date it can't satisfy crafted by virgin filaments. Scientists guaranteed that yarn can be utilized for particular utilize if squander is chosen in particular sums from the different waste classifications and combined legitimately. Endeavour on making Dreft yarns from reused strands likewise demonstrates great outcomes however as crude materials utilized is thoroughly squander materials so textures created obviously has a place with shabby textures which are recommended to be utilized as a part of the field of cleaning fabrics, wrapping fabrics and covering fabrics. (46)

3.5.3.2. Bio-composite and Nonwoven Materials

Protein fiber squanders, for example, by-products from the fleece material industry, low quality crude fleeces not fit for spinning, speak to a vital sustainable wellspring of biopolymers. Fleece fibers when damaged in their histological parts connecting the intercellular bond by ultrasonic-catalyst medications, the subsequent cells were implanted in a polymeric film-shaping network of cellulose acetic acid derivation, of acquiring new composite material, appropriate for film creation and fiber spinning. Cellulose acetic acid derivation is to a great extent utilized as a part of the generation of yarns for materials, channels, plastics; electrical protections, photographic movies, pigmented sheets, therapeutic and clean application since it display an exceptional protection from molds and microorganisms.

Recycled fibers can be viewed as traditional in specialized materials, especially in nonwoven. Recycled fibers are utilized as a result of low costs or in light of the fact that they only cover something up. In any case, recycled fibers are additionally connected in nonwoven to use exceedingly profitable practical segments.

3.5.4. Benefits of Textile Recycling

- Recycled garments lessen the landfill space. Landfill destinations represent a risk to the earth and water supplies. When it downpours, water depletes through the disposed of garments and grabs perilous chemicals and fades. This water ends up being lethal. Material produced using engineered fibers won't deteriorate rapidly though textures like fleece discharges methane, during disintegration and the two fibers eventually cause a worldwide temperature alteration. At the point when these textures are recycled, this risk will be diminished to a significant degree.
- It saves money on utilization of vitality, as recycled garments require not be recolored or sourced. Lessened utilization of colors and chemicals limits their make and eventually the unfavorable impacts of their production.
- It decreases cost of acquiring new materials and expands profit efficiency.
- It additionally limits the expenses of transfer of new virgin or crude materials and furthermore the ecological effects by decreasing utilization of new crude materials and delivering items from prior one.
- Textile recycling does not make any new unsafe waste.

3.5.5. Challenges of Textile Recycling

- There is no economical motivating force for waste makers to lessen squander.
- Low esteems, high transportation cost or absence of market interest for recouped materials especially.
- The power of little and medium recuperation and recycling undertakings debilitate interests in squander recuperation advancements.

3.5.6. Future of Recycled Textile Materials

Innovations in technology are being continuously investigated in the field of textile material recycling. A key hindrance to powerful recycling is the multiplication of textile materials in various fiber mixes that are hard to isolate for recycling, for example, cotton and polyester. Analysts have inspected how to isolate the cotton from the polyester utilizing earth sound ways to deal with breakdown of cotton so as to recover the polyester for recycling. Another boundary to successful recycling is the subsequent poor shading nature of low-grade. The dim dark grey of recycled fiber is unsuited to most attire applications or for sure for most broad items. A Japanese report proposes a shading coding to empower the subsequent low-grade to be all the more effectively handled into usable yarns. As both mechanical and chemical recycling innovations grow, more open doors may show up for CLR of materials inside attire, and also proceeded with OLR of materials into different items. Patterns towards natural concerns see shoppers more prone to anticipate that organizations will offer economical materials and think about the biological effects of their items.

Extensive retailers have the compass to gather utilized apparel at scale, and by taking a lead they show that they see the social incentive and additionally financial incentive in seeking after recycling alternatives. (47)

3.6. Wastes, Methods of Recycling and Labeling

Recycling, a well-known and widely used terminology, necessarily consists of both down-cycling and upcycling. Down-cycling and upcycling aim to prevent wasting potentially useful materials, reducing consumption of raw materials, energy usage, and reducing air and water pollution. Down-cycling is the process of converting waste materials or scrap products into new materials or products of lesser quality and reduced functionality. Examples of down-cycling may include making a rug from clothing wastes and producing lower-grade plastic from recycling. Upcycling, the term introduced by Reiner Pilz of Pilz GmbH in 1994, is the process of converting waste materials into new materials or products of better quality, for better environmental values. Upcycling has seen an increase in use due to its current marketability and the lowered cost of reused materials. Popular examples of upcycling include making a rug from fabric scraps and producing a new skirt from old denims. (48)

Stages	Process
Primary approach	Industrial scraps
Secondary approach	Mechanical processing of post-consumer products
Tertiary approach	Pyrolysis/hydrolysis of polymeric wastes to get monomers of fuels
Quaternary approach	Burning fibrous solid wastes and utilizing the heat generated

Table 11 - Approaches for recycling

Recycling technologies are divided into primary, secondary, tertiary, and quaternary approaches based on the raw materials used and the products produced at the end of the process (Table 11). (49)

All four approaches also exist for fiber and fabric recycling. The US Environmental Protection Agency (USEPA) estimates that textile wastes occupy nearly 5 % of all landfill spaces and the textile recycling industry recycles only approximately 15 % of postconsumer textile wastes (PtCTW) each year, leaving a huge 85 % waste in the landfills. It could be attributed to high (40 %) rates of postconsumer textile waste generation and low (2 %) diversion rates. Many organizations including the Council for Textile Recycling (CTR) are involved in creating awareness about keeping the postconsumer textile wastes out of the solid waste streams with a goal of achieving zero textile waste going to landfills by the year 2037. Textiles and apparel,

being the major chunk of materials in landfills, reusing and recycling postconsumer textiles and apparel are gaining international attention. (50)

Textile waste materials are broadly classified into three categories, including

- (i) pre-consumer textile wastes (PrCTW),
- (ii) postindustrial textile wastes (PITW), and
- (iii) postconsumer textile wastes (PtCTW).

Pre-consumer textile wastes are those wastes that never make it to consumers and which come directly from the original manufacturers. Following are the types of wastes that come under this pre-consumer textile waste category and the list is not exhaustive.

- Ginning wastes
- Opening wastes
- Carding wastes
- Comber noils
- Combed waste yarns
- Roving wastes
- Ring-spinning waste fibers
- Ring-spun waste yarns
- Open-end spinning waste fibers
- Open-end spinning yarn wastes
- Knitting waste yarns
- Weaving waste yarns
- Fabric cutting wastes
- Fabric wet-processing wastes
- Apparel manufacturing wastes

Postindustrial textile wastes (PITW) are generated during the manufacturing process of upstream products. These are mainly from the virgin fiber producers, tire cord manufacturers, polymerization plants, and other plastic products. Postconsumer textile wastes (PtCTW) are the wastes that come from the consumer and these are generally the clothes that are ready for disposal or landfill. They are recovered from the consumer supply chain. Favorite examples of the PtCTW include recycling of the accessories, beverage bottles to make recycled polyester. Preferences for recycling of wastes appear to be predominant in thermoplastic polymer-based fibers due to the ease of processability and the ability to take on different forms and shapes after recycling. Nevertheless, natural fibers such as cotton, wool, and silk are also finding their ways into the recycling stream in terms of both down-cycling and upcycling. The majority of the literature reported in the recycling of textile wastes includes polyester followed by cotton, flax, linen, polypropylene, polyethylene, nylon, p-aramid, carbon, silk, polybutylene terephthalate, bamboo and kenaf. The recovered fibers, then, find their way to friction spinning, rotor spinning, or comingling methods with various functional finishes such as flame retardancy and UV protection. Conversion of pre-/postconsumer textile wastes into final products consists of the following stages. (51)

- Collection and sorting
- Fiber extraction
- Yarn preparation
- Conversion into fabrics and composites
- Finishing

Recycled fibers, yarns, and fabrics made of different textiles and polymeric bottle wastes possess physical properties similar to that of virgin fiber-based products. Many times, recycled fibers are supplemented with the addition of virgin polyester fibers, organic cotton, flax, and

elastomeric fibers in order to achieve enhanced properties, aesthetics, and functional values. Many voluntary and nonprofit organizations make attempts to conserve natural resources through various campaigns and create awareness of both down-cycling and upcycling processes. Consumers are encouraged to use recycled products by creating esteem values (e.g., vintage look) for the products and providing labeling systems with different motives. With a view to conserve paper- and wood-based materials from postconsumer wastes, globally, a labeling system (Figure 15 a) has been introduced by the Forest Stewardship Council (FSC) an international nongovernmental organization dedicated to address various deforestation issues. (52)

The FSC supports both recycled and reclaimed substances; however, such labels are issued only to products that contain 100 % recycled materials.



Figure 15 - Labels for recycled products a Forest stewardship council, b Global recycle standard, and c Bluesign

The Textile Exchange (earlier known as the Organic Exchange) of Texas is another nonprofit organization established in the year 2002 with a commitment to expand textile sustainability in the textile value chain across the world. It has introduced the concept of Global Recycle Standards (GRS; Figure 15 b) modified recently in 2012, includes recycling of pre-consumer and post-consumer wastes and does not include preindustrial wastes inasmuch as many times such wastes are reintroduced into the main production stream and do not amount to recycling, instead diverting into the waste streams (e.g., wastes obtained in the drawing, roving, and spinning are reintroduced in the blow room or reusing the polymeric wastes back into the same process).

GRS provides a three-tier (level) system based on the total content of recycled material in the final products. The gold standard offered by the GRS is meant for products containing 95–100 % recycled materials, whereas silver and bronze standards include final products with recycled content of 70–95 % and a minimum of 30 %, respectively.

Bluesign is another labeling system (Figure 15 c) promoted by the Bluesign Technologies AG, Switzerland-based organization which also audits the manufacturing processes, energy inputs, and air emissions from various processes. Each component used in the process is examined based on eco-toxicological issues and the possibilities to reduce consumption and suggest the alternatives. Textile waste-processing units are expected to adopt verifiable procedures, processes for such labeling standards; Bluesign labels are issued to socially conscious versions of jackets, pants, shirts, sweaters, and accessories such as hats and gloves.

All these initiatives are expected to promote environmentally appropriate, socially beneficial, and economically viable management systems of various waste streams and waste materials from pre-consumer wastes, postindustrial wastes, and postconsumer wastes, in general. Many more players work on providing the labeling to recycled and reclaimed products. Textile waste recycling and reclaiming industries, which process significant amounts of waste generated globally, are expected to benefit from these standards on many fronts. (41)

Natural Fibers

Pre-consumer or postconsumer cotton wastes are again converted into yarns and subsequently to fabric forms. Fabric-breaking machines along with yarn-opening attachments help in opening up the fibers and the opened fibers are spun into coarser yarns by ring, rotor, and friction spinning processes.

3.6.1. Recycled Yarns

Yarn production from recycled materials paves the way for the production of fabrics and other value-added products. Various reports available on the production of recycled yarns suggest that yarns can be produced using friction spinning to produce a medium (50 s) count (linear density) yarn from the PET recycled fibers. Rotor spinning is another widely used spinning technique for the production of recycled yarns and, optimum opening roller speed for the successful spinning of polyester/waste blended rotor yarns has been recommended with other process parameters.

Comparison of yarns produced from recycled fibers and virgin fibers shows that tenacity and elongation values of yarns obtained from recycled fibers differ marginally, however, such processes appear to be economically advantageous in the long run. Nevertheless, spinning of recycled and reclaimed fibers using ring spinning has also been a favorite option for many manufacturers. (53)

3.6.2. Fabrics from Recycled Yarns

Recycled fibers and yarns are predominantly used in manufacturing home furnishings, reinforced concrete, and polymeric composites, towels, shoddies, carpets, floor coverings, wipes, accessories, nonwovens, and acoustic insulators.

Commercially, many manufacturers offer a wide range of woven/knitted/nonwoven fabrics manufactured from recycled materials (details are discussed below), however, very little information have been reported in the literature regarding their aesthetic, utility, and durability and comfort properties. A study carried out to examine the performance and durability of woven fabrics manufactured from recycled polyester fibers, extruded from PET bottle wastes, reveals that with an increase in the recycled polyester fiber content, bending rigidity and shear stiffness values increase. However, durability tests reveal that the bending rigidity and shear stiffness values decrease on repeated washing and fatigue measures such as higher hysteresis and lower resilience values are not clear. Another study of recycled T-shirt cotton fabrics reveals the effect of home laundering on the physical properties in comparison with virgin cotton fabrics of similar construction. T-shirt fabrics produced with recycled cotton fibers, compared to the T-shirt fabric produced from virgin cotton fibers, show a tendency to shrink in the course direction possess decreased air permeability, and a small change in

bending rigidity in the wale direction. Chlorine-based bleaches are successfully applied in bleaching of recycled cotton fabrics to eliminate the dirt and impurities associated with the fabrics produced from yarns without losing the properties significantly.

3.6.3. Concretes and Composites

Recycled fiber-reinforced composites using cotton, flax, kenaf, carbon, PET, and cement concretes using natural and HDPE have been developed in the past. Concrete structures, widely used for construction purposes, are relatively brittle with their tensile strength values typically about 1/10 of compressive strength values and regular concrete structures are generally reinforced with steel rods or bars of different dimensions and grades.

Composites made out of flax, cotton, and recycled polyethylene exhibit higher fabric strength with the increase of blend percentage of flax fibers obviously due to their inherent properties, although the elongation values decrease. Apparently, the effects of moisture on composites made from recycled composites have been analyzed.

Thin composite boards have been manufactured with the noils obtained from the cotton combing process, blowroom wastes, and polyester resin at room temperature utilizing a compression method. Tests on tensile and flexure properties of these composites reveal that composites made from cotton wastes are significantly much stronger than polyester matrix, and these composites show the potential to replace wood and fiber-board products as the thin boards.

3.6.4. Home Furnishings

Home furnishings have been the primary focus for using recycled fibers, yarns, and fabrics for many of the manufacturers and polyester, cotton, silk, aramid, and polypropylene fibers are widely used for various products. Pre-consumer textile wastes and postconsumer textile wastes are used equally in the production of home furnishings and postindustrial textile wastes are also gradually being introduced in such products.

Disposable and hygienic pillows have been developed with the filling made from 100 % recycled, expandable polyester and covered with non-allergenic nonwoven fabrics, which are further recyclable.

Regenerated Cotton Wipes from Rockline Industries (Wisconsin) won the Visionary Award for the most innovative use of nonwovens in consumer products for the year 2010. The USP of recycled cotton fibers includes variability in length, and use of dark colored and white fibers separately, in addition to other sustainable parameters (PITW). Composting of such recycled wastes degrades more than 90 % in 28 days.

Strateline Industries LLC (Arkansas) makes wet wipes from fibers recycled from fabric cuttings supplied by T-shirt factories located in various parts of China (PITW).

Cotton Incorporated has partnered with Bonded Logic Inc. of Arizona to collect discarded blue cotton jeans (PtCTW) for reprocessing into insulation materials that are donated for use in houses built by Habitat for Humanity. Similar concepts are also used by Blue Point Living (Florida) which offers recycled towels using the raw materials obtained from pre-consumer recycled cotton to the extent of 25 %. The recycled fiber yarns are manufactured using 65 % virgin cotton fibers, 10 % polyethylene terephthalate, and the remaining content from recycled cotton fibers.

MebRure Studio (Turkey) offers a wide range of eco-furniture manufactured using white oak and recycled silk coverings filled with spongy stuffs. Silk and spongy combinations are expected to provide a unique and luxurious experience to consumers.

Leigh Fibers of South Carolina has established manufacturing facilities to reprocess postindustrial fabric wastes of both natural and manmade fibers into products suitable for use in a wide range of nonwovens and other under-the-surface applications as well as for remelting and subsequent spinning into different linear densities. SafeLeigh flame-retardant (FR) aramid fibers recycled from postindustrial clippings provides the advantage of inherent FR properties for needle-punched and air-laid nonwoven furniture components, mattresses, and automotive parts. Blends are also produced using virgin and reclaimed waste materials, and synthetic and natural fibers. Various grades of fibers produced include grades for airlay where products are designed to be run on air-laid forming machines, grades for garneting, and, grades for blowing, where short fiber blends are designed for use in blowing applications. In addition to needle-punching, SafeLeigh products are amenable to processes including thermal bond and pad-making. It is also claimed that cotton, rayon, acetate, polypropylene, acrylic, and other textile wastes are used in many under-the-surface applications as well as wet wipes.

Newlife™, continuous polyester yarns from 100 % recycled post-consumption PET bottles mainly through mechanical processing, is seen as the source of the prestigious red carpets of the world, endorsed by divas and celebrities, on account of the collaboration with CLASS, Creativity, Lifestyle and Sustainable Synergy Manufacturers of Newlife claim the possibilities of using the yarns for different applications in every subset of technical textiles, including awnings, outdoor clothing, sportswear and technical outfitting, underwear, work wear, medical and protective clothing, home furnishings, and interior and outdoor design fabrics. Research work carried out on the developments of acoustic underlay products from recycled carpet wastes have shown positive results and reinforce the assurance for the commercially viable products. Laboratory trials performed on the recycled underplays, manufactured with recycled carpet wastes and styrene-butadiene binders are compared with commercially available products, produced with standard granulating PVC-back, nylon/polypropylene piles and binding.

Recycled underlay performs well in the ISO 140-8 test for impact sound insulation of floor coverings as well as BS 5808 specifications. Combinations with appropriate backing scrim in the recycled underlays ensure the impact performance of such materials and facilitate value-added products.

3.6.5. Branded Accessories and Apparel

Levi's lifecycle assessment of 501 jeans and Dockers, conducted in the year 2007 paved the sustainability roadmap for the coming years. The surprising results indicate that nearly 50 % of water is consumed in cotton harvesting, another 45 % of water is used by consumers during washing, and nearly 60 % of the energy is used in making and taking care of a pair of jeans. Levi's Waste-Less™ Jeans consist of at least 29 % postconsumer recycled plastics made from eight plastic bottles. Levi's Waterless™ denims aim at reduction of water consumption during manufacturing and are produced by using ceramic stones, rubber balls, and changing the filtration system in the washing machines to enhance mass transfer actions, which facilitates the reduced water consumption. A distressed look is achieved with just four liters of water, whereas normal styles require up to 45 liters of water per pair of denim jeans.

Nike, with its sports jerseys for the 2010 FIFA World Cup that were made from recycled plastic bottles, has created awareness of sustainability across the globe in a positive manner and Flyknit, an innovative manufacturing process that reduces waste in knitted fabrics is used in the upper parts (shoe uppers) of shoes.

Adidas is well known for its association with the London Olympics 2012 in making the world's first truly sustainable Olympics initiatives. Fluid Trainer, the most sustainable shoes ever as claimed by Adidas, is designed in such a way that it reduces waste in shoe upper designs. Adidas jointly with Carvico and Aquafil, produces high-performance swimwear from 100 % recycled polyamides from postconsumer materials, suitable for swimsuits and trunks.

Hera Bamboo low-cut socks is a sustainable invention by Asics, made up of a blend of recycled polyester fibers and bamboo fibers. Asics Men's ARD SS Run Shirt adds another feature, a finish with recycled coffee grounds that facilitates UV protection with a UPF of 50+.

Most of the garments manufactured by Espirit (Hong Kong) are from either 100 % organic cotton, or cotton in conversion or organic linen or Tencel or a blend of these fibers, from as early as 1992.

Marks & Spencer unveiled its first Shop coat, made from recycled fabrics collected through its Shopping initiative, where customers can drop in unwanted items of clothing regardless of brands and values. It is said to have collected about 6 million items through this initiative, whose benefits are passed on to Oxfam, a nonprofit organization that helps to find solutions to mitigate poverty across the world.

Puma's Bring Me Back program has played a great role in the recycling process. Puma's InCycle is a sustainable collection that includes shoes, apparel, accessories, and home insulation materials made up of either biodegradable polymers, or recycled polyester and organic cotton.

Gucci (Italy) has earned its reputation by developing sustainable eyewear manufactured from liquid wood, a composition of bio-based materials that represent an alternative to plastic-based materials. Now, it has come to the sustainability forefront, with its new Sustainable Soles, a line of footwear made with biodegradable plastics sourced from the composting process.

3.6.6. Sustainable Brands on Focus

Many leading brands are now considering the impact of their production process on the environment. Hence, they have initiated recycling or reusing process into their manufacturing facility to reduce their environmental impact. The initiatives of the few brands, on sustainability are provided with their adapted method.

- **Evrnu™** has made an imaginative new innovation that reuses cotton clothing waste to make premium, sustainable fiber called as "pristine new fiber". The company basically converts all collected solid wastes into fluid and then processes into unadulterated fiber that can go up against the requirements of the designers and product development team. They had likewise asserting that they are making this with 98% less water than it takes to make conventional cotton fiber and with 90% lessened CO2 emanations contrasted with polyester generation.
- **Fabscrap** offers easy pickup and recycling of textiles in New York City. They had tie up lots of leading fashion brands, independent designers, cutting rooms, textile arts organizations,

schools, and regional processors. They intend to develop a system of up-cycling and down-cycling organizations to guarantee greatest diversion from landfill.

- **ReRoll**—ReRoll creates flat textile goods made from cutting room scraps. Scrap materials are gathered from manufacturing plants, production facilities and designers and the procedure means to end the inefficient practices of the garment industry. It pays attention towards transforming fabric “scraps” or “waste” into resource or a raw material for new production. The studio was established by creator Daniel Silverstein. His point, the Zero Waste is a mission to kill inefficient form of industry standards by alternative fashion made using his unique procedure.

- **TONLE'**—The organization begins their procedure with scrap sourced from mass textile manufacturing industries. They make handcrafted apparel and adornments marked by their Cambodian producers. But still, Tonlé working hard to take out their last 2–3% of waste in processing, so that they can make the organization really zero waste industry. The greater part of the process is they convert their pieces of fabric waste which cannot be used in design, as recycled paper. These papers again used to make the “Tonlé” hangtags.

- **Ecotec**—Is an Italian company, which develops recycled yarn from pre dyed cotton textiles, sourced as a scrap out of fashion and clothing manufacturing house. They also produce traceable yarns. Traceable yarns means, the customer learn about the farm/industry and the source of the farm/industry that produced the yarn, by simply entering yarn information printed on the label. The company claims that they consume 77.9% less water than the similar textile manufacturing companies. This is due to the colored yarn production, which totally eliminates the dyeing process, there by the manufacturer reduces the environmental impact.

- **Trmtab**—is one of the apparel trim recycling company which works on leather scraps from production facilities in India, specifically the leather trims that are the byproduct of leather goods production, and turns them into woven and chevron stitched accessories like wallets and clutches. The manufacturing industries reject the leathers with scares, marks, and other natural defects. These kind of good leathers were graded as second and third class only due to their look and appearance. This kind of leather waste will be recycled into useful fashion accessories by the Trmtab.

- **Patagonia** has for quite some time been a pioneer in sustainable textiles. They manufactured first outdoor clothing by consolidate reused plastic containers into their line of fleece products, in 1993. Now the company uses their processing plants to repurpose cotton scraps, converting into fabric and apparels. The organization guarantees the scraps from 16 virgin cotton shirts can be transformed into one recovered cotton shirt.

- **Pure waste textile**—They assert that for creating 1 kg of cotton it required 11000 L of water and by doing reuse they diminish the effect of cotton waste and water utilization. The raw material is gathered from two primary sources, (1) cutting wastes from article of clothing manufacturing industries and (2) yarn scraps from spinning/weaving factories. The wastes were sorted out by quality and color. Every quality/color is mechanically opened once again into fibers. The fibers can be blended with chemically recycled polyester or viscose filaments to achieve a particular usefulness relying upon the end utilization of the clothing (Chhabra 2016).

- **Nike**—The leading sportswear manufacturing company claims that, in the year 2015 alone they have 54 million pounds of factory scrap was transformed into premium materials used in Nike performance footwear and apparel. Nike uses recycled materials in their 71% of footwear and apparel products, in everything from yarns and trims, to soccer kits and basketball shoes.

3.7. Current status of textile reuse and recycling

The interest in increased textile reuse and recycling is consistent with the increased attention being given to the circular economy concept in international and national policy.

In the textile industry, reuse and recycling (in the form of down-cycling) is already well established. For example, in Europe about 15-20% of disposed textiles are collected (the rest is landfilled or incinerated), whereof about 50% is down-cycled and 50% is reused, mainly through exporting to developing countries. There are, however, large variations within Europe: more prominent examples are Germany, in which about 70% of disposed textiles are collected for reuse and recycling, whereof a fraction is separated for incineration, and Denmark, in which about 50% is collected, mainly for reuse domestically or abroad. Still, there is a great potential to further increase reuse, as clothing items typically are disposed of long before the end of their technical service life. Considering the low recycling rate today, there is a great potential to also increase recycling, particularly polymer, oligomer and monomer recycling, thereby preventing textile waste that cannot be reused or fabric/fiber-recycled from being landfilled or incinerated. Polymer, oligomer and monomer recycling is, however, hindered by a lack of technologies for sorting and separation into pure enough fractions although there have recently been significant breakthroughs in the separation of cotton/polyester blends. There are also numerous non-technical barriers for increased textile recycling. (36)

If the recycled material is of lower value (or quality) than the original product, this is termed down-cycling. Today, existing textile recycling routes are in most cases down-cycling. Clothing and home textiles are down-cycled into, for example, industrial rags, low-grade blankets, insulation materials and upholstery. In contrast, if a product from recycled material is of higher value (or quality) than the original product, it is termed upcycling. As the length of the fibers and the constituent molecules are reduced by wear and laundry, fabric and fiber recycling typically yields materials of lower quality (if quality is defined in terms of fiber quality) than materials made from virgin fibers (unless mixed with yarn from virgin fibers). Thus fabric and fiber recycling are typically considered to be down-cycling. In contrast, polymer, oligomer and monomer recycling typically yields fibers of similar quality to virgin fibers. It should be emphasized that just because fiber and fabric recycling are examples of down-cycling (in terms of fiber quality), they are not necessarily less preferable from a waste hierarchy perspective compared to polymer, oligomer or monomer recycling. In contrast, a cascade approach could be optimal, in which the textile waste first enters fabric or fiber recycling, and once the fiber length has been reduced to a level at which the material is not fit for fabric or fiber recycling, it enters polymer, oligomer or monomer recycling. Another classification for recycling routes is into closed- or open-loop recycling. Closed-loop recycling refers to when the material from a product is recycled and used in a (more or less) identical product, whereas open-loop recycling (also called cascade recycling) refers to processes in which the material from a product is recycled and used in another product. A "product" can here refer to different levels of refinement, which means that a given recycling route may be referred to as either closed- or open-loop recycling, depending on context. For example, something that is a product in a B2B context (e.g. a fiber or a fabric) may not be in a retail or consumer context (where garments are key textile products). The latter viewpoint would imply that closed-loop recycling relies on, for example, a T-shirt being recycled into a T-shirt or even a T-shirt of a certain size, color and, perhaps most importantly, quality (e.g., fiber length) being recycled into a T-shirt of the same size, color and quality. In contrast, a more lax definition of closed-loop recycling could, for example, be that a material category (such as packaging) is recycled into the same material category rather than another.

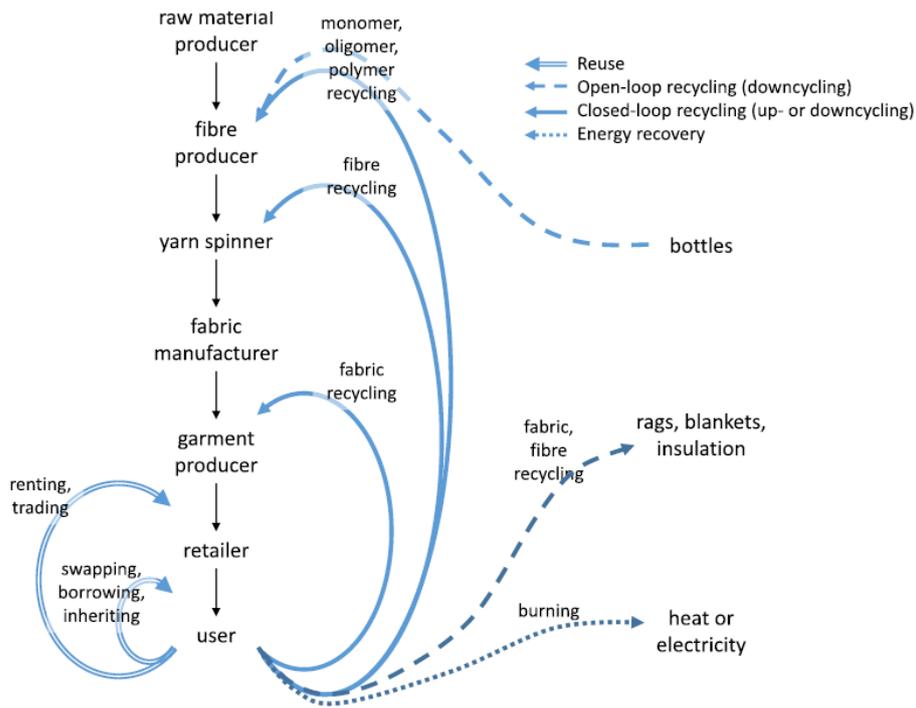


Figure 16 - A classification of textile reuse and recycling routes

Cotton is the most studied material (covered in 76% of the studies) both for studies of reuse and recycling, followed by polyester (63%), also counting bottle-to-fiber recycling, viscose (25%) and wool (20%). Other materials are studied in no more than a few publications each. The preponderance of studies on polyester and cotton reflects the domination of fiber markets by these fibers and they occupy about 51% and 24% of the global market, respectively. Figure 17 provides an overview of the prevalence of different material in studies of reuse and certain recycling routes. The above percentages could be underestimates as at least one the studied reused/recycled materials is not specified in four of the publications, and information on the type of recycling is missing in six.

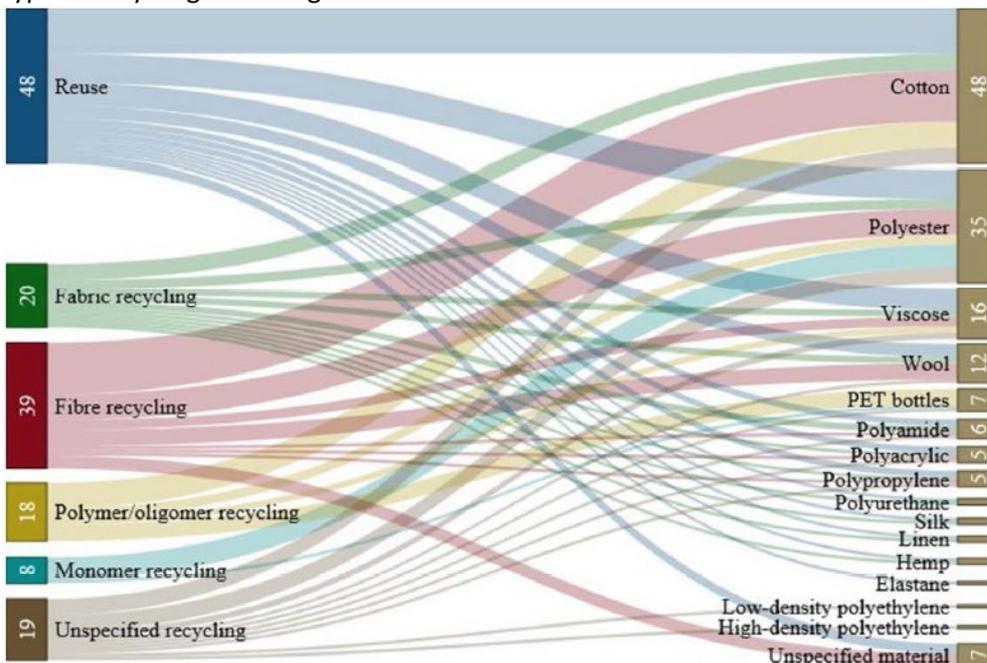


Figure 17 - Prevalence of combinations of studied reuse/recycling routes (36)

3.8. Development of antimicrobial textiles

The development of antimicrobial textiles has been one of the most active and important research areas in recent years, involving activities in the discovery and applications of new antimicrobial agents, novel functional fibers, new chemical finishes, and nanotechnologies. Antimicrobial textiles are expected to be able to address many challenges ranging from increased spreading of infectious diseases, especially drug-resistant ones, across the world, including bacteria, viruses, spores, and fungi, to the concerns on regular hygienic issues such as odor generating microbes on apparels and sportswear, as well as conservation needs of textile artifacts and the life of geotextiles. Because of vastly diversified applications of the antimicrobial textiles and expected functions for intended uses of the textiles, significant progresses in the development of novel antimicrobial agents and technologies have been achieved in recent years.

Antimicrobial functions on textiles span from inhibiting growth of microorganisms to inactivating pathogens rapidly, distinct differences in the power of the functions as well as in desired applications. Thus, textiles with the microbial inhibition ability are also described as biostatic functional materials, while those possessing the rapid bacterial kill functions are called as biocidal textiles, which could mark the difference in antimicrobial functions. At the same time, these terms could remind people of the potential applications of the textiles. Biostatic functions are suitable for the conservation of textile artifacts and odor-control sportswear and may not be able to provide the desired biological protective functions for humans. Antimicrobial textiles for medical applications and for human protections against biological agents should offer biocidal rather than biostatic functions since the textiles are expected to completely and quickly eliminate the pathogens by contact. Any residual pathogens on the textiles could still transmit diseases and cause infections.

In addition to the power of antimicrobial functions on textile products, the durability of the functions is a tough challenge, especially the washing and storage durability. Differing from other functions on textiles, antimicrobial agents or functions are consumed daily and continuously since fabrics and clothing are always in surface contact with microorganisms. The options to solve the challenge are either incorporating an unlimited supply of the agents to textiles or frequently replenishing the agents on the textiles, otherwise the functions could be lost as the products are used and left in the air during storage. In order to incorporate antimicrobial agents to textiles in more durable ways, microencapsulation, plasma treatment, and sol-gel technologies are practical methods, and the application of silver or other metal nanoparticles could offer prolonged release of biocidal metal cations.

Besides, textiles have intimate contact with human skin, and the antimicrobial agents on the surfaces of the textiles could cause skin irritation and sensitization reactions, bringing in human safety concerns. Beyond the human safety concerns, released antimicrobial agents into the environment are persistent and may affect microbes in the environment. These two aspects are discussed in the chapters "Life cycle assessment (LCA) of reusable hospital textiles with biocidal finish" and "Antimicrobials for protective clothing." Human skin hosts many healthy microorganisms, which provide protections against pathogens as well. The biocidal functional textiles might be able to lead to the complete elimination of microorganisms on human skin, which might damage the human natural protection system and cause harmful consequences to humans. (54)

3.8.1. Antimicrobials and textiles

Textiles, fabrics, and apparel are subject to a range of microbial challenges. The base fabrics, auxiliaries, and the intended uses can all affect the antimicrobial performance of the textile. In general, synthetic fibers are resistant to microbes because they are not of the natural world and do not have antagonists that have evolved to break them down. Many are also hydrophobic and do not provide the moisture necessary for microbes to flourish. If spinning oils from natural sources are left on synthetic fibers, the possibility of microbial growth on the surfaces does exist. Natural fibers such as cotton and other cellulose, wool, silk and other protein-containing fibers, and manufactured cellulose such as rayon and lyocell with their high moisture regain are susceptible to attack.

For a given textile, each auxiliary, material, and performance characteristic may affect how well an antimicrobial works, and depending on how the textile is used, how long the antimicrobial will actually last. Another factor that enters in will be the intended function of the antimicrobial. Durability to wear and to both home and commercial laundering are essential where apparel is the textile in question.

Commonly requested antimicrobial textile tests include AATCC 30-III—quantitative for antifungals, AATCC 100—quantitative for antimicrobials, and AATCC 147— qualitative for antimicrobials. Durability testing is recommended (55).

3.8.2. Definitions and the use of the term antimicrobial on textiles

One of the more important questions (perhaps the most important) is whether a textile product can be labeled as being “antimicrobial” after it is treated with an antimicrobial agent. Such a product may be subject to federal environmental laws and state laws that regulate “pesticide” products. For example, the Federal Insecticide, Fungicide, and Rodenticide Act, referred to as FIFRA may apply to the product. The United States Environmental Protection Agency (EPA)’s definition of a “pest” includes any “fungus, bacterium, virus, or other microorganism”. A product that addresses these pests and attempts to kill or mitigate them is a pesticide and may have to be registered with the EPA. Because such a registration can be difficult for a specific product, rather than the chemical itself, a product that has been treated with an antimicrobial agent usually takes the path of marketing these products under the EPA’s treated articles exemption.

The treated articles exemption was created by the EPA to allow for the distribution of products that may be useful but also would be hard to register because of the difficulty of demonstrating adequate efficacy. However, in order to take advantage of the treated articles exemption, the antimicrobial product used within the treated article must be registered for that use. By exempting these products, the agency has allowed the use of minimal pesticide-related claims, such as “antimicrobial” and “kills odor-causing bacteria,” on products that are not registered. Registration of pesticides for use in treated articles is generally easier than registering new pesticide products. The treated articles exemption allows for the distribution of products that have specific usefulness as long as broader claims about their effect on their surroundings are not claimed.

3.8.3. History of antimicrobials applied to textiles

The application of antimicrobials to textiles dates to problems in World War II in the hot and wet South Pacific when cotton fabrics used for tents and tarpaulins rotted and fell apart at an

alarming rate. It was soon determined that a filamentous fungus (*Trichoderma reesei*) was the source of the problem. This fungus easily degraded the cotton material into lower saccharides and glucose by action of the cellulose and hemicellulose enzymes it secreted. A number of different treatments were designed to fight this deterioration of the cotton. These included various mixtures of waxes that were either chlorinated and/or had copper and antimony salts added to them. For the time being, these treatments were somewhat successful though they stiffened the fabric and often had an objectionable odor. As many have pointed out, the environmental and toxicity negatives of these treatments were not focused on at that time.

As long as cotton was the primary fiber used in outdoor military and industrial fabric applications, research on antimicrobials was centered on the chlorinated phenols and copper salts. Alternative treatments to these were focused on chemically modifying the cellulose molecule itself by acetylation or cyanoethylation. Most of these modification processes had the disadvantages of cost of both the chemicals and the equipment needed for application. The added costs in an industry where profit margins are traditionally low discourages their application. The other very significant factor was the growing introduction of synthetic fibers into military and industrial markets, which by their very nature were not attacked by fungi and bacteria from the natural world.

Although treatment of textile materials for outside uses still has great relevance, the major interests in antimicrobials on textiles have to do with concerns about nosocomial infections (those gained in hospital stays), various home health care products, water purification, doctors and dental offices, and more recently, consumer goods marketed as preventing odors from forming on items of apparel.

3.8.4. Conventional antimicrobials applied to textiles

Historically, conventional antimicrobials applied to fibers and fabrics fall into about five categories. These are quaternary ammonium compounds, halogenated phenols, chitosans, polybiguanides, and N-halamines. The desired use of the textile often dictates which of these agents is applied. *Quaternary ammonium compounds* (see Figure 18) are cationic surface active agents and can be applied to surfaces of fibers that have an anionic charge in water. They have been widely used as disinfecting agents in other applications. Depending on how they are modified, they can be active against a wide variety of gram-positive and gram-negative bacteria. They work by having the cationic ammonium part of the molecule disrupt the negatively charged cell membrane of the microbe in question.

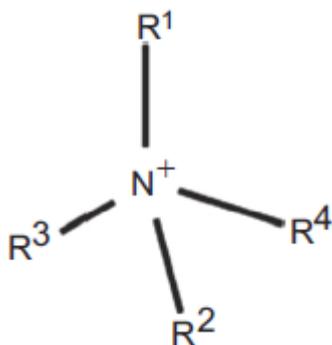


Figure 18 - General structure of quaternary ammonium compounds

Chitosan is the deacetylated derivative of chitin (Figure 19 and 20), the main component of various crustacean shells. Given the size of the seafood industry, this waste product is available in large quantities.

Studies of chitin have shown it to have very effective antimicrobial properties against most common bacterial species. This activity can be affected by the degree to which deacetylation proceeded and by the molecular weight. The mechanism of the antimicrobial activity of chitosan probably relates to the primary amine in the structure which can accept a positive charge and interact with the negative charges on the surface of the microbe. This results in disruption of the cell wall and loss of cell integrity.

Polyhexamethylene biguanide (PHMB) is a broad spectrum bactericide with low toxicity (Figure 21). Both cellulosic and synthetic fibers have been treated with PHMB though the synthetics usually need a cross-linking resin included to increase durability. The biguanides attack the cell membrane with increasing activity as the molecular weight increases.

A more recent addition to the antimicrobial concepts have been the heterocyclic compounds, N-halamines (Figure 22). They have at least one covalent bond between a nitrogen and a halogen, usually chlorine. They are effective as a biocide because the Cl^+ ion is released in water and binds to the microorganism. This then interferes with metabolic pathways and kills the microorganism. The resulting N-H bond can be regenerated by dilute sodium hypochlorite. The N-halamines are thus rechargeable antimicrobials. If vinyl reactive groups are added to the N-halamine, then these compounds can form permanent attachments that allow repeated recharging.

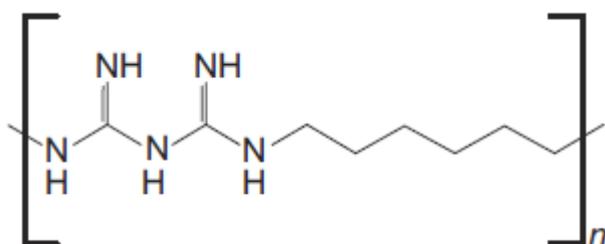


Figure 19 - Structure of chitosan.

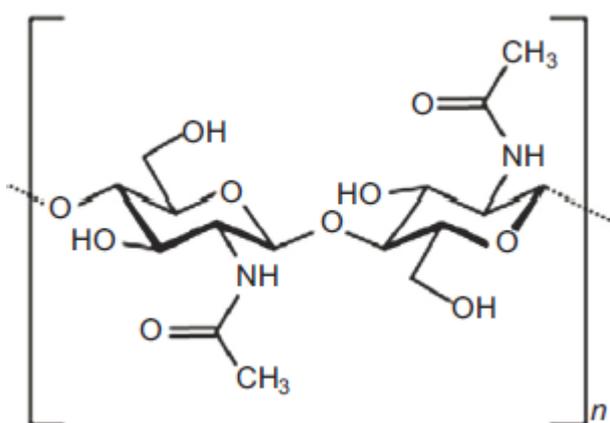


Figure 20 - Structure of deacetylated chitosan-chitin.

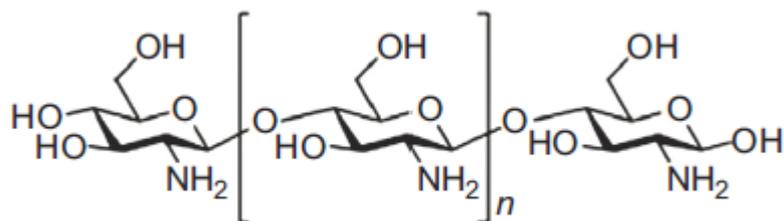


Figure 21 - General structure of polyhexamethylene biguanide

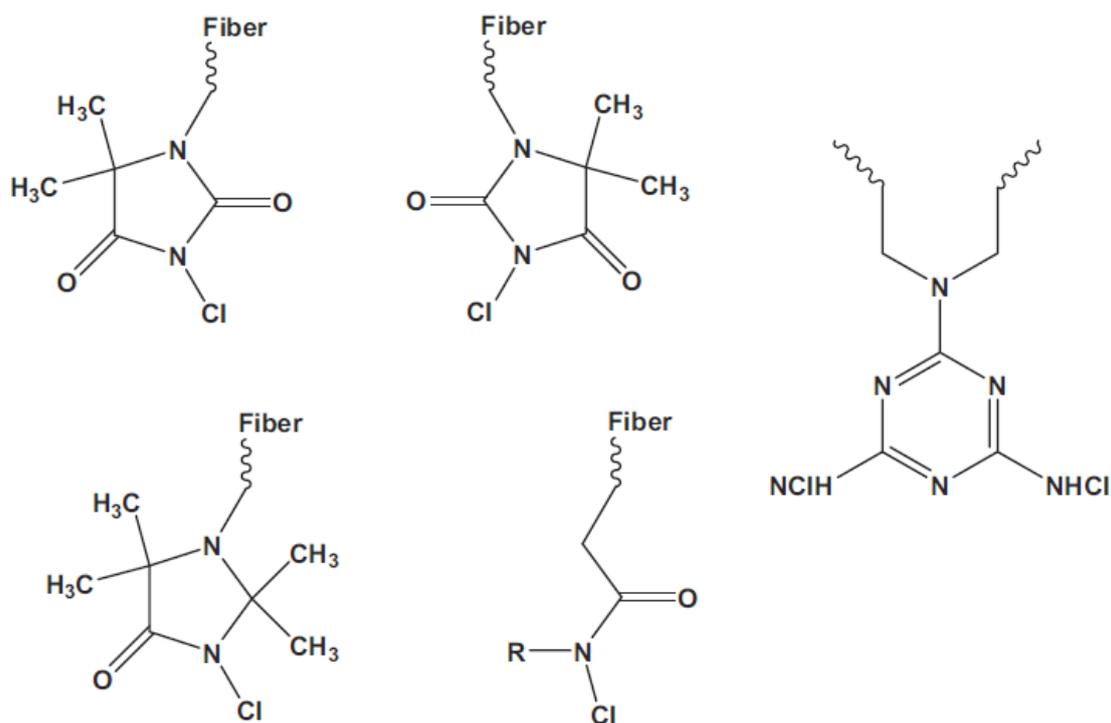


Figure 22 - General structure of N-halamines.

3.8.5. Nanotechnology and antimicrobial treatments on fibers

Nanotechnology presents the ability to create very small particles with very high specific surface areas. In addition, at the nano level some materials take on properties not seen at the micro or macro level. A number of metal and metal oxides have been produced as nanoparticles that show promise as antimicrobial agents. These include silver, titanium dioxide, zinc oxide, and copper II oxide.

The antimicrobial properties of metal particles are a combination of the high specific surface area, which provides great opportunity for a reaction with microbes, along with the increased solubility that comes with the greatly increased specific surface area. In the case of TiO₂, microbes are killed by photocatalytic action. Clearly, for textiles with their close proximity to the human skin, the question of toxicity of metal oxides is of paramount importance in their use, regardless of their inherent antimicrobial properties.

Silver is easily the most common nanoparticle used in consumer products. It is used in respirators, water filters, cosmetics, cutting boards, shoes, cell phones, laptop keyboards, and children's toys. It is also by far the nanomaterial most widely used in clothing and textiles.

There is a long history of using silver in various forms for the treatment of water and for wounds and burns. Potable water has been a historical concern, and there is evidence that the Phoenicians, as early as 1200 BC, knew that silver vessels could help make water safe for drinking. Silver nitrate has been extensively used for medical treatments that have included venerable diseases, burn treatment, and eye problems in infants. Varying levels of silver have been used in wound dressings as concern has increased regarding the antibiotic-resistant bacteria.

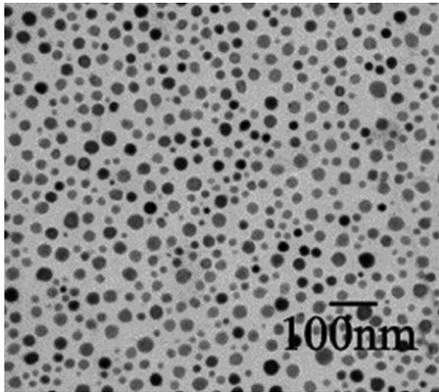


Figure 23 - Highly monodisperse silver nanoparticles.

The mechanism by which nanoparticle silver works as an antimicrobial is not fully understood. The action is related to a reaction with moisture, whereby the inert metallic state silver is ionized and becomes highly reactive. A mechanism usually cited is the release of silver ions from the nanoparticles, uptake of the ions which then disrupt adenosine triphosphate (ATP) production and DNA replication. Another mechanism is generation of oxidative species by the silver nanoparticles and ions, which then attack the microbe cell wall. In general, silver nanoparticles are effective against most bacteria, including *Escherichia coli*, *Staphylococcus aureus*, *Staphylococcus epidermis*, *Bacillus subtilis*, *Klebsiella mobilis*, and *Klebsiella pneumonia* among a number of others. These particles are also effective against fungi such as *Aspergillus niger*, *Candida albicans*, and *Saccharomyces cervisia* and against some viruses. Various silver nanocomposites with dendrimers and polymers, as well as silver loaded into zeolites, show antibacterial effects. (55)

3.9. Textiles used in medical environments

A wide variety of textile items can be found in the hospital environment. Bed linens, blankets, uniforms, scrubs, patient gowns, mattresses, curtains, seating, towels, and cloths are all used. Other items such as gloves, aprons, eye visors, caps, and shoe covers can all be used as personal protective equipment (PPE) to provide protection to the patient and staff member administering treatment. PPE items are most commonly disposable and in the UK are sent for incineration after use, having been placed into clinical waste bins. As well as providing protection for staff and patients, PPE items, such as aprons, are also used to protect the uniform during a shift. Where heavy soiling or contamination of uniforms occurs, it requires an immediate change, and wearing an apron can help prevent a member of staff having to change their uniform several times during a shift (56).

3.9.1. Clothing

Clothing in medical settings takes the form of staff uniforms and gowns provided to patients. The clothing worn by staff ranges from dresses, tunics, and trousers on a ward environment to

scrubs suits (reusable or disposable) worn in theaters. The style of uniform clothing can vary throughout hospitals in the UK, with colors also ranging from white, gray, green, red, and blue, often with different trims and components. Uniforms are worn to provide protection to the wearer, as well as ensuring a professional image of staff. Uniforms also act to minimize the risk of infection spreading, along with ensuring staff can safely move patients and/or equipment while maintaining the safety of patients.

The use of antimicrobial treatments on medical uniforms is of growing interest, and tunics/trousers which utilize silver ion technology are readily available to healthcare providers. Limited evidence is available on the effectiveness of antimicrobial treatments on nurses' uniforms in a clinical setting.

3.9.2. Bedding

Bed linen found in hospitals is most commonly made from 100% cotton or 50% cotton/50% polyester fabrics in a plain woven construction. Heavier-weight blankets can also be provided and are produced using 100% cotton for comfort. The use of 100% polyester mattress covers with a polyurethane (PU) coating is popular to aid in cleaning after use.

Although antimicrobial coatings are not applied to bedding items, this route of decontamination is taken to ensure that microorganisms are removed during laundering. This also helps to reduce the potential of cross contamination and survival of microorganisms on bedding.

3.9.3. Furnishing items

Curtains are used to separate cubicles, providing patient privacy, and can be treated with fire retardant finishes such as Proban (for 100% cotton fabrics) or Trevira CS (for 100% polyester fabrics). Technologies such as "shield™ plus" (a nonleaching antimicrobial), provided by Panaz healthcare, are purported to be effective against a range of microorganisms, having been tested to AATCC 147-2004, with no visible growth under the fabric reported against Methicillin Resistant *Staphylococcus aureus* (MRSA), *Klebsiella pneumoniae*, *Escherichia coli*, and *Clostridium difficile* spores. This technology is readily available through providers such as Curtain Call, who supply several National Health Service (NHS) Trusts in the United Kingdom with curtains and products treated with "shield™ plus".

3.9.4. Dressings

A popular choice for wound dressings and bandages is 100% cotton, due to the high absorbency properties of the fiber, and they can be woven, knitted, or nonwoven, depending on the application. It is noted by Salah et al. that wound dressings need to be flexible, permeable, and able to absorb fluids while controlling water loss. Bandages must be durable and supportive to patients, as well as close fitting, which makes knitted structures more suitable than woven fabrics for this type of application.

In modern medicine, it has become more commonplace to find wound dressings with antimicrobial treatments applied to improve wound healing. Honey is an example of a natural antimicrobial used in wound dressings, and its effectiveness has long been reported in the treatment of surgical wounds, trauma wounds, diabetic leg ulcers, and partial thickness burns. The strongest antibacterial honey available is Medihoney and in clinical practice is the most commonly used alongside Manuka honey. The use of silver in wound dressings is also a

popular choice, as stated by Leaper, with availability in forms such as creams, foams, hydrogels, films, and meshes.

3.10. Antimicrobial finishing agents for textiles in medical environments

Many antimicrobial agents are available commercially; however, not all are suitable for use on textile items, which have specific requirements. When applied to textile surfaces, antimicrobials can work in two ways: diffusion and contact. Diffusion antimicrobial agents work by migration, and the active agent spreads across the surface, thus inhibiting the growth of microorganisms. Contact antimicrobial agents, in comparison, are non-migrating, and the microorganism must come into direct contact for the antimicrobial agent to be effective.

When applied to textiles, it is important that antimicrobial treatments fulfill several basic requirements:

1. Safety to the consumer by using low toxicity products
2. Not causing allergies or irritation to the skin
3. Not causing any negative impact on textile properties or appearance
4. Being compatible with textile processing methods
5. Providing durability to laundering processes

These properties are therefore important when considering antimicrobial treatments which are applied to textiles and subsequently used in medical environments to ensure user safety as well as functionality of the treated product (56).

3.10.1.1. Commercially available antimicrobial finishes for medical textiles

3.10.1.2. Quaternary ammonium compounds

The use of quaternary ammonium compounds (“quats”) is common in the medical market as they have proven disinfectant properties and can be used to sanitize surfaces. Their effectiveness can be reduced when exposed to hard water or materials such as cotton and gauze pads. The compounds work by causing the inactivation of energy-producing enzymes along with disrupting the cell membrane and denaturing cell proteins. Quats are generally reported to be fungicidal, bactericidal, and virucidal against lipophilic (enveloped) viruses; however, they are not sporicidal or virucidal against hydrophilic (non-enveloped) viruses. Efficacy of quats against gram-negative bacteria is reduced and can also be inactivated when exposed to anionic detergents (57).

Aegis enhanced is a popular antimicrobial treatment found on medical textiles and is a quaternary ammonium compound-based finish. The treatment works through fixing a nano-coating onto the surface of a fabric, and microorganisms are deactivated on contact. The application of Aegis treatments to textiles can take place in three ways:

1. Spraying
2. Exhaustion
3. Padding

The treatment also achieved the Oeko-Tex standard in 2004, which means that it is included on the list of approved active chemical products for textiles and complies with safety standards. A variety of products can be coated with quats-based treatments and are readily available (for example, curtains, drapes, scrubs, face masks, and wound dressings).

3.10.1.3. Metals Silver

Silver is also a popular choice of antimicrobial, and it is used as an antibacterial and antifungal agent. The silver ions are able to inhibit bacterial growth and cell division, as well as damaging the cell envelope (cell wall and inner cell membrane) through binding to groups of enzymes. The use of silver as an antimicrobial agent also extends past textile items, as it can be found in washing machines to improve hygiene and reduce the potential for cross contamination to occur, as it is effective against a broad range of microorganisms including bacteria and viruses. Its integration into food packaging, apparel, shoes, and water treatment facilities has also been reported. In an “in vitro” setting, it is reported that within 30 min, silver can destroy gram-positive and gram-negative bacteria as well as VRE and MRSA. In a study conducted by Smith et al., it was observed that for fabrics containing silver, soaking wet conditions were required for activation and efficacy, leading to the recommendation of use within products where surrounding conditions would be wet.

Copper

Copper has long been recognized as an antimicrobial, and its use within textiles is of growing interest. The use of copper is popular in medical areas, including the control of *Legionella* in water distribution systems. It is reported to be fungicidal, antibacterial, and antiviral, with the ability to damage a microorganism’s envelope, intracellular proteins, and nucleic acids.

To try and prevent the survival and spread of microorganisms on surfaces, the use of copper has also been tested to determine its effectiveness when placed in a hospital environment.

3.10.1.4. Chitosan

Chitosan is the deacetylated derivative of chitin, which is originated from the shells of shrimp, crabs, and other crustaceans. Chitosan has a pKa of ~6.5 because of the amino groups in the molecules. It is positively charged and soluble in acidic to neutral solutions. Its antimicrobial activity mainly comes from the positively charged amino groups, which enable chitosan to disrupt the cell membrane integrity as a result of interaction with the negatively charged bacteria surface. Besides antimicrobial activity, chitosan also exhibits some favorable properties such as biodegradability, biocompatibility, and nontoxicity.

Chitosan can be chemically linked with cotton fibers using a cross-linking agent such as citric acid, butanetetracarboxylic acid (BTCA), or Arcofix NEC (low formaldehyde content). An alternative way to attain chemical bonding is to oxidize cotton with potassium periodate to generate dialdehyde groups and then make the aldehyde groups couple with the amino groups of chitosan (Figure 24). Because of its positive charges, chitosan can also be deposited onto cotton fibers through its electrostatic interaction with an anionic polymer, eg, poly(sodium-4-styrene sulfonate), using a layer-by-layer self-assembly technique. The antimicrobial activity of chitosan can be enhanced by quaternary ammonium derivatization, and various chitosan *derivatives* have also been used for textile finishing (Figure 25). (57).

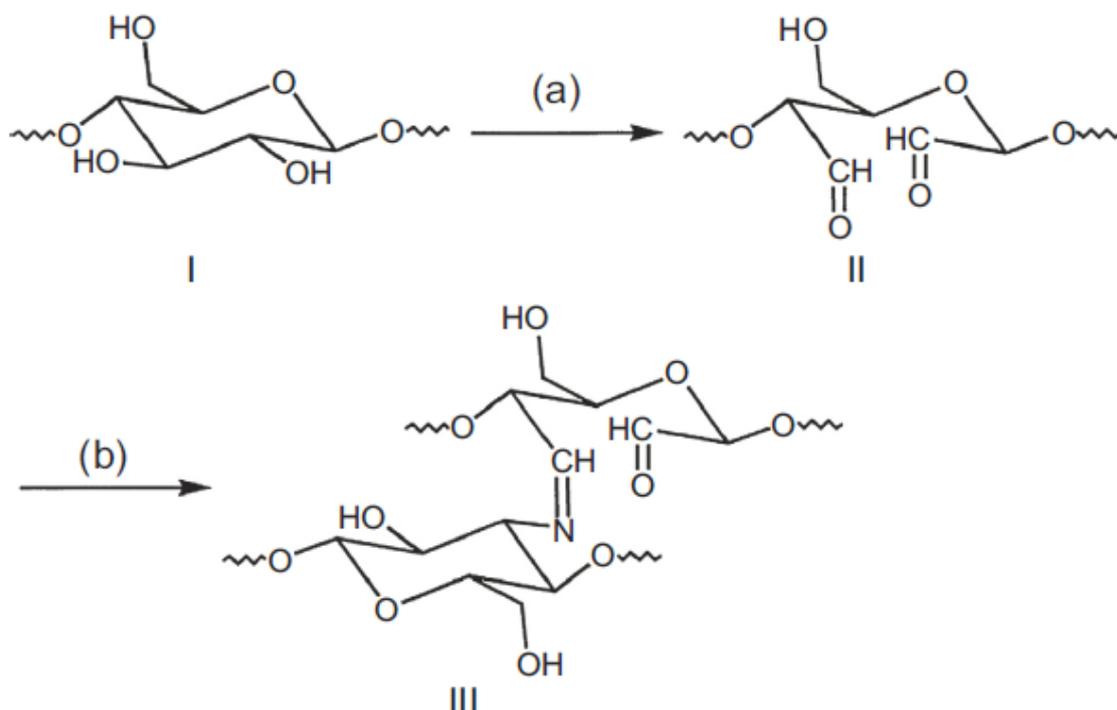


Figure 24 - The oxidation of cotton with potassium periodate (a) and the reaction of the generated aldehyde group with the amino group of chitosan (b).

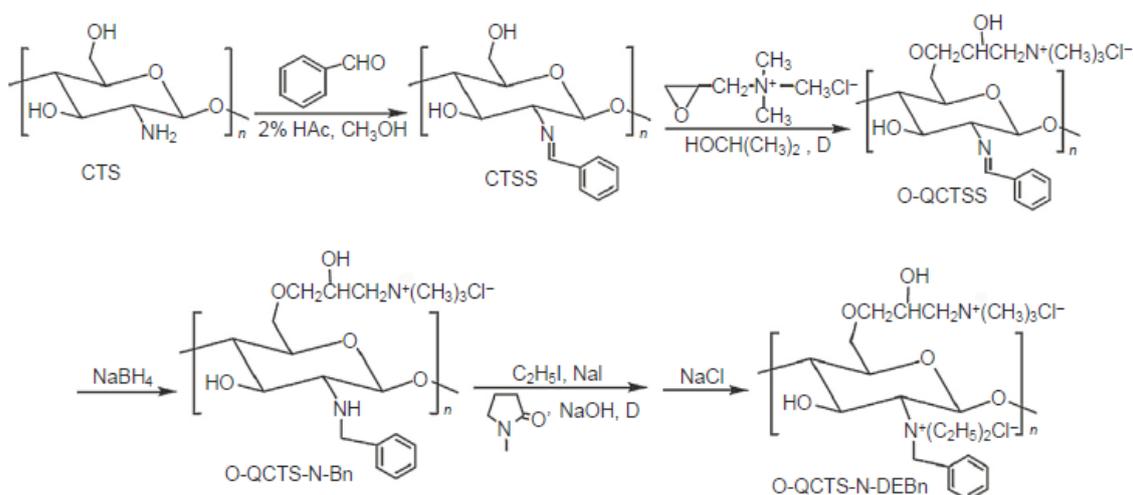


Figure 25 - Synthetic route of chitosan derivatives.

3.11. Methods of testing efficacy of antimicrobial textiles

Once an antimicrobial treatment has been developed and applied to a textile, it is important to determine how effective it is. The aftercare of textiles, including laundering temperatures and the use of detergents, can all impact upon the effectiveness of an antimicrobial product during the life of a textile item. Testing products which are unwashed and have been exposed to subsequent washing procedures is therefore necessary to gain an understanding of efficacy across the item's life (56).

3.11.1. Testing standards

In order to determine the efficacy of antimicrobial treatments, various standard test methods and protocols are available. However, there is not a specific British Standard for testing the efficacy of antimicrobial agents on textiles, although standards are available to test products such as disinfectants.

Methods developed by the American Association of Textile Chemists and Colorists (AATCC) and the American Society for Testing and Materials (ASTM) can be used to assess the antimicrobial efficacy of treatments applied to textiles under various conditions. As previously discussed, antimicrobial agents can work by diffusion and contact methods. It is, as a result, appropriate for methods to assess both ways in which antimicrobial agents can work.

Two popular standards, developed by the AATCC, which are used for testing antimicrobial treatment efficacy are AATCC 100, Assessment of Antibacterial Finishes on Textile Materials, and AATCC 147, Assessment of Antibacterial Finishes on Textile Materials via the Parallel Streak Method (AATCC, 2011).

For testing antimicrobial efficacy under aqueous conditions, the ASTM have developed the ASTM E-2149-10 Standard test method for determining the antimicrobial activity of immobilized antimicrobial agents under dynamic contact conditions (ASTM, 2010). To gain a full assessment of the antimicrobial activity, the standard also specifies to carry out the AATCC 100 and AATCC 147 test methods (56).

3.11.2. Efficacy testing

Regarding customer satisfaction, marketing, and registration (United States), it is very important that the textiles show a proven antimicrobial effect. For this the effectiveness of antimicrobial textiles can be determined by various standardized methods with different experimental setups. A distinction is drawn between qualitative and quantitative test methods. In the following a selection of the most important methods for antibacterial and antifungal testing is presented (58).

3.11.3. Antibacterial testing

3.11.3.1. AATCC 147 (parallel streak method)

This method describes a simple and qualitative test for determining the efficacy of diffusible antibacterial agents on textiles. It is not suitable for materials which tend to encapsulate and prevent the diffusion of the antibacterial agent. Because of its simple test design, this method is only useful for obtaining a first assessment of antibacterial activity. Within the scope of this standard, no limit values for zone of inhibition and antibacterial activity are specified.

Nutrient agar plates are inoculated with *Staphylococcus aureus* ATCC 6538 or *Klebsiella pneumoniae* ATCC 4352, but other suitable microorganisms can be used as well. The inoculation is carried out by immersing an inoculation loop in a bacterial suspension and transferring the inoculation loop to the surface of the agar plate by making five parallel streaks. Afterward, the antibacterial textile or a control sample without an antibacterial agent is pressed gently on the inoculated agar surface. The samples are incubated for 18–24 h at 37 °C. An antibacterial effect will be displayed by an inhibited bacterial growth underneath the antibacterial textile and a possible zone of inhibition around the textile in comparison to the control sample (59).

3.11.3.2. DIN EN ISO 20645 (agar plate diffusion test)

The agar plate diffusion test is also used for qualitative evaluation of antibacterial efficacy of textiles. A semi-quantitative evidence of efficacy can be achieved by a comparison of different concentrations of the same antimicrobial product. For successful investigations of antibacterial efficacy the textiles have to be finished with diffusible antibacterial agents. Due to the categorization of the antibacterial textiles the efficacy (no effect, limit of effect, good effect) can be specified.

A petri dish is filled with a layer of nutrient agar, which has to solidify afterward. For preparing the top layer, nutrient agar is inoculated with a suspension of *S. aureus* ATCC 6538, *K. ATCC* 4352, or *Escherichia coli* ATCC 11229 and poured on top of the lower agar layer. The antibacterial textile and a control sample are cut in discs (four samples of front and back parts of the textiles) with a diameter of 25 mm and placed on the solidified bacterial agar. The samples are incubated for 18–24 h at 37 °C. Based on the size of the inhibition zone around and bacterial growth underneath the textile, the antibacterial efficacy can be evaluated. According to this standard, the textile already shows a good antibacterial effect if there is no inhibition zone and no growth (gram-negative and gram-positive strains) underneath the antibacterial textile (60).

3.11.3.3. ASTM E2149 (shake flask test)

The shake flask test is a quantitative challenge test for non-leaching antimicrobial textiles in a bacterial suspension under dynamic contact conditions. On the basis of the obtained results a percent reduction in comparison with an untreated control is calculated. Although this is possible, no limit values for antibacterial efficacy of the textiles are specified within this method.

According to ASTM E2149-13a, the antibacterial efficacy of textiles is determined with *E. coli* ATCC 25922, but other suitable microorganisms can be used. A sample of the antibacterial textile and an untreated control are placed in a bacterial solution and agitated at maximum stroke for one hour with a wrist-action shaker. Alternative contact times can be used depending on the end use of the product. The concentration of the bacterial solution is determined at the beginning (without textile contact) and after contact time. Following the incubation period for 24 h at 35 °C the percent of bacterial reduction is calculated. In addition to the antibacterial efficacy a possible leaching of the antimicrobial is determined (61).

3.11.3.4. AATCC 100

AATCC 100 describes a quantitative test for antibacterial textiles. After incubation of an inoculated untreated control or an inoculated antibacterial textile a percent reduction is calculated. Within the scope of this standard, no limit values for antibacterial activity are specified.

The antibacterial textile and an untreated control of the same fabric are cut in circular swatches with a diameter of 4.8 cm. The swatches are placed in a petri dish and covered with 1 mL of inoculum with *S. aureus* ATCC 6538 or *K. pneumoniae* ATCC 4352. So many swatches of the control or the antibacterial textile are added until the whole inoculum is absorbed. After this, the swatches are placed in a 250 mL wide-mouth glass jar which is closed. The swatches are incubated for 18–24 h at 37 °C. For enabling bacterial count, 100 mL of neutralizing solution is added and after shaking the resulting solution is plated on nutrient agar plates. The

concentration of the bacterial solutions are determined at the beginning and after contact time, and on the basis of these results a percent reduction is calculated (62).

3.11.3.5. DIN EN ISO 20743

This standard comprises three, relatively complex methods (challenge tests) for quantitative evaluation of antimicrobial textile efficacy against *S. aureus* ATCC 6538 and *K. pneumoniae* ATCC 4352 with completely different experimental setups. Depending on the antibacterial textile, the user defines the most suitable method. Limit values for antibacterial efficacy are specified for all three methods.

1. Absorption method

A bacterial suspension is pipetted on textile samples (six of the antibacterial and six of a control sample, each 0.4 g) in a little flask which is closed afterward. This approach is incubated for 18–24 h at 37 °C. The bacterial concentrations on three textile samples are determined, each at the beginning and after contact time.

2. Transfer method

Nutrient agar plates are inoculated with a bacterial suspension, and after wetting the whole surface, the liquid is removed subsequently. The antibacterial textile and an untreated control are cut each in six discs with a diameter of 38 mm. These samples are placed on the inoculated agar plates and weighed down with a 200 g steel cylinder. After this the samples (three of each textile) are placed with the inoculated side facing up in a petri dish. The incubation is carried out for 18–24 h at 37 °C in a humidity chamber. The bacterial concentrations on the textile samples are determined at the beginning and after contact time.

3. Printing method

According to this method, bacteria are placed on a membrane filter and are printed with a special device on a textile or control sample with a diameter of 60 mm. After this, the samples are placed with the inoculated side facing up in the lid of a nutrient agar plate. The incubation is carried out for 1–4 h at 20 °C and 70% relative humidity. The bacterial concentrations on the textile samples are determined at the beginning and after contact time.

By means of the amount of remaining bacteria on the antibacterial textile and the control at the beginning and after contact time, the antibacterial efficacy “A” is calculated:

$$A = (\log Ct - \log C0) - (\log Tt - \log T0) = F - G$$

A, antibacterial efficacy; F, value for bacterial growth on the control textile ($F = \log Ct - \log C0$); G, value for bacterial growth on the antibacterial textile ($G = \log Tt - \log T0$); log Ct and log Tt, logarithm of arithmetic mean for bacterial count of three samples after incubation for 18–24 h (log Ct, control textile; log Tt, antibacterial textile); log C0 and log T0, logarithm of arithmetic mean for bacterial count of three samples directly after inoculation (log C0, control textile; log T0, antibacterial textile) (63).

According to Table 12 the efficacy of antibacterial properties of the textile is classified.

Efficacy of Antimicrobial Properties	Values for Antimicrobial Efficacy A
Insufficient	$A \leq 2$
Significant	$2 \leq A \leq 3$
Strong	$A \geq 3$

3.11.4. Antifungal testing

3.11.4.1. AATCC 30

AATCC 30 is a semi-quantitative test and consists of four different methods for assessment of the susceptibility of textile materials to mildew and rot (test I and II) and of their antifungal activity (test III and IV). Within the scope of this standard, no limit values for inhibition of fungal growth or alteration of textile properties are specified.

1. Test III

This method is designed for the evaluation of antifungal activity of hydrophilic textiles. The antibacterial textile and an untreated control are cut in two discs with a diameter of 38 mm. A suspension of *Aspergillus niger* ATCC 6275 is spread on a nutrient agar plate which is subsequently covered with a textile disc. After this, fresh *A. niger* suspension is spread on the textile surface. This approach is incubated for 14 days at 28 °C, and the percentage of surface area of the discs covered with the growth of *A. niger* is evaluated.

2. Test IV

In this test, the antifungal activity of hydrophobic textiles is analyzed. A suspension comprising spores of *A. niger* ATCC 6275, *Penicillium varians* ATCC 10509, and *Trichoderma viride* ATCC 28020 is distributed on strips (2.5 × 7.5 cm strips or 2.0 × 2.0 cm strips; saturated with nutrient solution) of antifungal and untreated textiles. These strips are fixed in a french square jar bottle with water and incubated for 14 days at 28 °C. The fungal growth on the textile strips after different time intervals is evaluated (64).

3.11.4.2. DIN EN 14119

This standard describes four different procedures for the evaluation of fungal effects on textiles. The antifungal activity (process B2) is investigated with a qualitative test method. According to this standard the inhibition of fungal growth is classified, but there is no statement regarding limit values for antifungal activity of the textile.

Liquid nutrient agar is inoculated with a spore suspension of *A. niger* ATCC 6275 or *Chaetomium globosum* ATCC 6205 and poured in petri dishes. After solidifying, each of four textiles, which are cut in discs with a diameter of 30 mm, is placed on agar surfaces with either *A. niger* or *C. globosum*. After incubation for 14 days at 29 °C the inhibition zone around the textile and fungal growth underneath the textile is evaluated (65).

3.11.5. Assessment of antimicrobial testing methods

Although the efficacy testing of antimicrobial textiles is indispensable, there is a big disadvantage of the currently available methods: the lack of practicability. All these methods simulate optimum efficacy conditions for antimicrobial agents under high relative humidity or in contact with moist nutrient media. But these conditions, except sportive activities, normally do not occur during practical wearing or environmental processes of textiles. Thus it is possible that textiles will be regarded as antimicrobial, but under practical wearing or environmental conditions, there is no or a highly reduced antimicrobial effect. Another problem is that not every antimicrobial agent on the textile shows an antimicrobial action with every test method. Thus the comparability of the different methods is complicated additionally (58).

3.11.6. Durability testing

In the interest of consumers, the efficacy of antimicrobial textiles should remain constant for as long as possible, preferentially for the whole lifetime of the textile. The durability of antimicrobial textiles depends, among other things, on the application method of the antimicrobial, the stability/consumption, and the concentration of the antimicrobial. The reduction of antimicrobial concentration on the textile results obviously in loss of effectiveness.

In order to evaluate the durability of antimicrobial textiles the antimicrobial efficacy has to be tested after different washing cycles and storage times in the laboratory. For this the antimicrobial efficacy is determined at the beginning and at the end of the durability tests. If the antimicrobial activity decreases significantly, a low durability of the antimicrobial textile is proven.

Regarding wash durability testing, an appropriate washing process has to be chosen depending on the future application of the textile, eg, in the work wear (DIN EN ISO 15797) or leisure sector (DIN EN ISO 6330). In general, the remaining antimicrobial activity is evaluated after 50 washing cycles. Regarding storage stability testing the manufacturer has to choose between real time (eg, 25 °C; 60% humidity; 12–36 months) or accelerated aging (eg, 40 °C; 75% humidity; 3–9 months) of the textile.

Because no standard (or at least standardized) directives were available for durability testing until now, the manufacturers have to define the terms, like number of washing cycles, storage conditions, or data for remaining antimicrobial activity. This is why the results for durability testing of different manufacturers are poorly comparable (58).

3.11.7. Resistance risks

In general, a resistance is the acquired ability of an organism to resist the effect of a chemotherapeutic agent to which it is normally susceptible. Resistances in microorganisms can occur after exposure to sub-lethal doses of antimicrobial agents for short periods of time. Microorganisms develop diverse resistance mechanisms to neutralize or destroy antimicrobial agents. Due to their ability of transferring these properties to other microorganisms, the resistances spread.

Against the background of increasing numbers of antibiotic resistant microorganisms, antimicrobial textiles are used more and more often, especially in hygienically demanding areas, in the hope of minimizing the amount of infections. Unfortunately, microorganisms with resistances against antimicrobial agents (eg, silver-based compounds, zinc pyrithione, and triclosan) have been described. But the effectiveness of such microbial resistances depends on the availability of the antimicrobial agent (bound or unbound) and the present resistance mechanism in the microorganism (eg, export of the agent or inactivation with enzymes). Because many antimicrobial agents are incorporated in or bound covalently to the fiber, the uptake of these substances in microorganisms is not possible. Accordingly an export mechanism would not protect the microorganism against the antimicrobial. Hence, the presence of resistant microorganisms does not necessarily mean that these microorganisms are resistant against antimicrobial textiles.

It should be noticed that resistances against antimicrobial textiles have not been described explicitly, but there has been proof that some bacterial species and strains are not affected by antimicrobial textiles (58).

3.12. Health and environmental impacts

3.12.1. Human health

Although the purpose of antimicrobial finishing is health protection, the safety and toxicity of antibacterial agents should be considered, and their skin sensitization and irritation are also important factors because of the possibility of direct contact of the textile with skin. Actually, many antibacterial agents have adverse effects on humans. For instance, Ag is a heavy metal, though it has a relatively low toxicity to humans. Upon contacting with skin, Ag NPs can migrate into the body, accumulate and damage tissues like the liver and lungs, or even penetrate the blood–brain barrier.

Concerns have been raised to triclosan over the potential for endocrine disruption. It may disrupt thyroid hormone homeostasis and the reproductive axis. QACs are widely used in household and industrial products and do not have any severe effects on human health. Although there is no concern of skin irritation for Ag and *N*-halamines, evidence of skin sensitization was reported for QACs and triclosan (57).

3.12.2. Environmental impacts

Repeated laundering of textiles tends to release antimicrobial agents into aquatic ecosystems, and their accumulation could harm aquatic organisms. Ag is a non-degradable metallic material, but it can be immobilized by forming sulfide complexes, which are insoluble and much less toxic than Ag or Ag NPs. The formation of silver sulfide could reduce the concern for the toxicity of silver-based antimicrobial agents to aquatic resources. QACs are toxic to many aquatic organisms including fish, algae, rotifer, daphnids, and microorganisms used for wastewater treatment. QACs are generally considered biodegradable, but the degradation process varies depending on their concentrations, chemical structures, state of complexing with anionic surfactants, and microbial acclimation. PHMB also shows toxicity to some aquatic species. Although triclosan is not toxic to wastewater microorganisms at concentrations lower than its aqueous solubility, its degradation results in more toxic products such as dioxins, chlorophenols, and chloroforms than triclosan itself.

3.12.3. Microbial resistance

When using an antimicrobial agent, it is also important to consider the potential for the development of microbial resistance. Antimicrobial agents with multiple action modes generally have a lower risk of resistance development, while this risk is higher when the antimicrobial agent has a single mode of action, particularly when this mode of action is the same as that of antibiotics used in clinic. Laboratory studies have shown that some antimicrobial agents such as QACs, triclosan, and Ag can induce resistance development for certain microorganisms. However, there is still a lack of evidence on whether these antimicrobial agents can lead to resistance development in real life (57).

3.13. Barrier textiles for protection against microbes

3.13.1. Normal skin barrier and related flora

The skin is the largest organ of the human body, with approximately 2 m² surface area. It interfaces between the internal tissues of the body and the external environment to provide essential protective functions, such as barrier protection, thermoregulation (maintaining heat and moisture), antimicrobial defenses, and the specific and the nonspecific immune system.

Numerous microorganisms, called skin flora, reside on normal skin. A major nonhuman skin flora is *Batrachochytrium dendrobatidis*. These are usually nonpathogenic and either commensals (not harmful to their host) or mutualistic (offering a benefit). Skin and skin flora exhibit a mutualistic, or symbiotic, relationship: human skin provides sebum (lipids), sweat (minerals), and dead skin cells (proteins) to the resident flora. In turn, the resident flora may strengthen the skin's first line of defense. Natural skin surface pH averages 5, which is beneficial for its resident flora. The benefits that bacteria can offer include preventing transient pathogenic organisms from colonizing the skin surface, either by competing for nutrients, secreting chemicals against them, or stimulating the skin's immune system (66).

3.13.2. Disrupted skin barrier and pathogen colonization

The normal skin barrier is a very complex system formed by a tremendous number of interrelated components. The modification of any of these components results in altered barrier function, which culminates in a mild-to-lethal phenotype. Therefore altered barrier function is a central event in various skin alterations and diseases such as atopic dermatitis (AD).

AD is a multifactorial, heterogeneous genetic disorder with skin lesions characterized by a Th-2 cell-mediated response to environmental factors. AD patients exhibit defects in innate and acquired immune responses, and the disrupted skin barrier promotes skin colonization by microbial organisms, most notably *Staphylococcus aureus*, found in over 90% of skin lesions and unaffected skin. The degree of the density of colonized *S. aureus* and skin infections is largely attributed to abnormalities in adaptive immunity and is associated with the frequency and severity of cutaneous inflammation. Permeability and antimicrobial dysfunctions, two well-known facets of barrier abnormality, are coregulated and interdependent. Failure of the permeability barrier favors secondary infection, whereas pathogen colonization and infection further aggravate the barrier abnormality. Also, Staphylococcal superantigens (SsAgs), exotoxins produced by *S. aureus*, can penetrate the skin barrier and play a key role in the exacerbation and persistence of the inflammation.

3.13.3. Antimicrobial therapy and related textiles

There is a growing interest in the use of antimicrobial agents to target primary bacterial colonization and infection for the management of AD. Topical and/or oral antimicrobial therapy has been shown to be important for the treatment of AD in those who suffer from secondary bacterial infections with symptoms/signs. However, the therapy is not effective in preventing AD flare-ups.

Prevention and nonpharmacological treatment is becoming an increasingly desirable goal for the management of AD. The skin lesion care of AD requires protections against physical, chemical, and microbiological stresses to minimize primary and secondary infectious microorganisms and provides for an optimized healing environment. Clothing, often called "the second skin," covers most parts of the body and not only provides an additional shield for the body, but also creates a portable living microclimate that improves human survival. Antimicrobial active textiles, appropriate fabrics treated with antimicrobial agents, play a

significant role in achieving this goal in the primary care of AD patients. Clothing made from natural fibers, such as wool and synthetic polypropylene fibers, has abrasive effects that cause skin sensitivity and/or irritation and worse in the inflammatory skin conditions of AD. Thus it is important to carefully choose suitable fabrics to prepare antimicrobial textiles for various dermatitis subjects who have disrupted skin.

Cotton is the most commonly used textile and is frequently recommended by dermatologists for patients with AD because of its natural abundance and its inherent properties, such as good folding endurance and better heat conduction. The fact that it is easily dyed and has excellent moisture absorption is an added advantage. However, its structure contains short fibers which expand and contract, causing a rubbing movement that can irritate delicate skin. Cotton fabric structure analysis shows that interlocking fabrics provide relatively poor physiological comfort compared to jersey and rib fabrics. Rib fabrics possess better low-stress mechanical and thermal properties. Dyes used in cotton garments can increase the potential risk of a sensitivity reaction. Cotton is also prone to bacterial and fungal attack. In contrast to the short, stubby fibers of cotton, natural silk has long fibers, producing a fabric that is perfectly smooth and without skin friction. Silk garments are often closely woven, which impedes the flow of air and reduces the excessive sweating and moisture loss that can worsen xerosis when in direct contact with the skin. Some people are also allergic to the sericin protein in silk. Thus silk fabric is generally used for clothes that are not particularly useful in the care and dressing of children with AD (66).

3.14. Classification and mechanism of antimicrobial agents

Fabrics treated with antimicrobial agents play critical roles in protective and therapeutic devices for proper skin lesion care. Antimicrobial agents are bacteriostatic, bactericidal, fungistatic, or fungicidal. They also offer special protection against the various forms of textile rotting. Products with antimicrobial textile finishes can be classified into two types, based upon their antimicrobial mechanisms and their mode of attack on microbes. Table 15.1 summarizes the classification and mechanisms of antimicrobial textile finishes.

Type 1: The bound—(or contact, non-leaching type)—mechanism. The antimicrobial agents are chemically bound to fiber surfaces. These products can control only those microbes that are present on the fiber surface, not those in the surrounding environment. Thus the antimicrobials do not become depleted and, potentially, may have higher durability than diffusion mechanism antimicrobial textiles. However, compounds on a treated fabric may be abraded or deactivated with long-term use and lose their durability. Quaternary ammonium compounds (QACs), polyhexamethuylene biguanide (PHMB), chitosan, and *n*-halamines fall into this category (67).

Type 2: The controlled release—or diffusion, leaching type—mechanism. The antimicrobial agent is released from a reservoir either on the surface of the fiber or in the fiber and disperses slowly in a humid external environment to reach the microorganisms and inhibit their growth. An advantage of leaching antimicrobials is their superior antimicrobial activity compared to compounds that use other modes of action on the same fabric under similar environmental conditions. However, eventually the reservoir will be depleted and will no longer be effective. In addition, the antimicrobial that is released to the environment may interfere with other—desirable—microbes, such as those present in waste treatment facilities. Metal salts (silver, copper, and zinc) and halogenated phenols (triclosan) are examples of antimicrobial agents that utilize the diffusion mechanism (68).

Biocide	Fiber	Mechanism	MIC	Toxicity	Fiber interaction
QACs	Cotton Polyester Nylon Wool	A variety of detrimental effects on microbes, including damage to cell membranes, denaturation of proteins, and disruption of the cell structure	10–100 mg/L against gram-positive and gram-negative bacteria	Moderate to highly toxic	Covalent bonding very durable Possible bacterial resistance
PHMB	Cotton Polyester Nylon	Impairs the integrity of the cell membrane and increasing levels of polymerization	0.5–10 ppm, broad spectrum bactericidal agent	Moderate acute aquatic toxicity	Large amount needed Potential bacterial resistance
N-halamines	Cotton Polyester Nylon Wool	Biocidal functions via chemical modification processes to interfere acceptors on microorganism walls, enzymatic and metabolic processing	N/A	Moderate to highly toxic	Needs regeneration Odor from residual chlorine
Chitosan	Cotton Polyester Wool	Inhibit the growth of microbes	0.05–0.1% (w/v) against many common bacterial species	Adverse effect on handle	Low durability
Silver	Polyester Nylon Wool Regenerated cellulose	Damage bacteria cell membrane, displace Ca ²⁺ and Zn ²⁺ ions, interact with sulfur, oxygen, or nitrogen	0.05–0.1 mg/L against a broad range of gram-positive and gram-negative bacteria	Little to nontoxic	Slow release Durable but Ag can be depleted
Triclosan	Polyester Nylon Polypropylene Cellulose acetate Acrylic fiber	It inhibits microbial growth by blocking lipid biosynthesis	<10 ppm against many common bacterial species	Breaks down into toxic dioxin.	Large amount needed; bacterial resistance.

Table 13 - Classification and mechanisms of antimicrobial textile finishes

3.15. Chitin and chitosan: Chemistry, properties and applications

Chitin is the second most ubiquitous natural polysaccharide after cellulose on earth and is composed of $\beta(1\rightarrow4)$ -linked 2-acetamido-2-deoxy- β D-glucose1 (N-acetylglucosamine) (Figure 1). It is often considered as cellulose derivative, even though it does not occur in organisms producing cellulose. It is structurally identical to cellulose, but it has acetamide groups ($-\text{NHCOCH}_3$) at the C-2 positions. Similarly the principle derivative of chitin, chitosan is a linear polymer of $\alpha(1\rightarrow4)$ -linked 2-amino-2-deoxy β -D-glucopyranose and is easily derived by Ndeacetylation, to a varying extent that is characterized by the degree of deacetylation, and is consequently a copolymer of N-acetylglucosamine and glucosamine (Figure 27).

Chitin is estimated to be produced annually almost as much as cellulose. It has become of great interest not only as an under-utilized resource but also as a new functional biomaterial of high potential in various fields and the recent progress in chitin chemistry is quite significant (69).

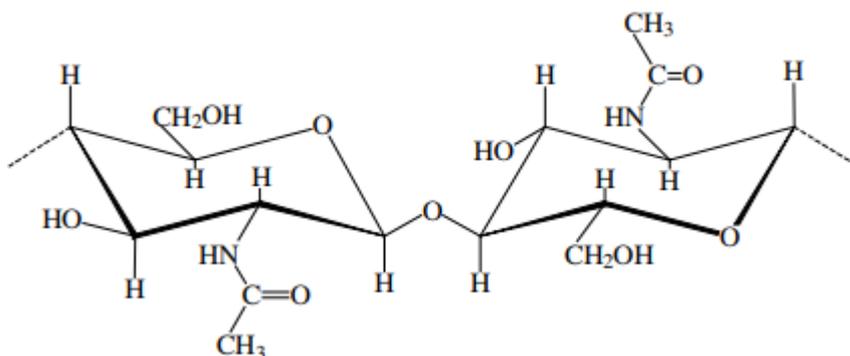


Figure 26 - Structure of chitin

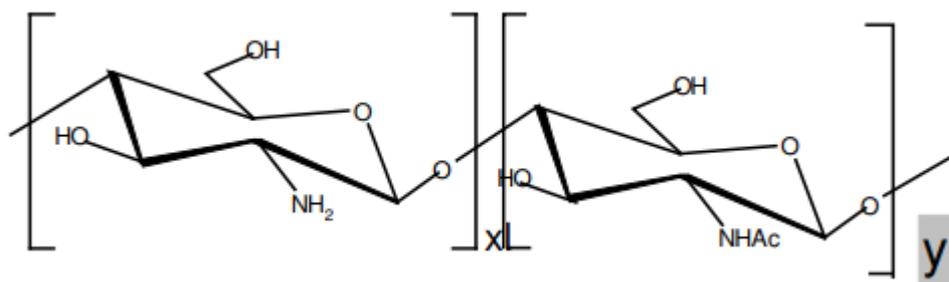


Figure 27 - Partially deacetylated chitin

Chitin is a white, hard, inelastic, nitrogenous polysaccharide found in the exoskeleton as well as in the internal structure of invertebrates. The waste of these natural polymers is a major source of surface pollution in coastal areas. The production of chitosan from crustacean shells obtained as a food industry waste is economically feasible, especially if it includes the recovery of carotenoids. The shells contain considerable quantities of astaxanthin, a carotenoid that has so far not been synthesized, and which is marketed as a fish food additive in aquaculture, especially for salmon.

The chitinous solid waste fraction of average Indian landing of shellfish was ranged from 60,000 to 80,000 t. The three parts of our motherland, India, are surrounded by ocean and its inner land is also very much rich with ponds, lakes, and lagoons. The proper utilization of those water resources (aquaculture) in terms of research in chitin and chitosan can bring the economic and academic prosperity of the nation. Chitin and chitosan are now produced commercially in India, Poland, Japan, the US, Norway and Australia. A considerable amount of research is in progress on chitin/chitosan world over, including India, to tailor and impart the required functionalities to maximize its utility.

Chitin and chitosan the naturally abundant and renewable polymers have excellent properties such as, biodegradability, bio-compatibility, non-toxicity, and adsorption. The reaction of chitosan is considerably more versatile than cellulose due to the presence of -NH₂ groups. Various efforts have been made to prepare functional derivatives of chitosan by chemical modifications, graft reactions, ionic interactions, and only few of them are found to dissolve in conventional organic solvents.

Chitosan is only soluble in aqueous solutions of some acids, and some selective N-alkylidinations and N-acylation have also been attempted. Although several water-soluble or highly swelling derivatives are obtained, it is difficult to develop the solubility in common organic solvents by these methods.

Modification of the chemical structure of chitin and chitosan to improve the solubility in conventional organic solvents has been reviewed by many authors. On the other hand, only a few reviews have been reported on biomedical applications of chitin/chitosan and no comprehensive review has yet been published covering the entire range of applications. The present review covers the literature from 1993 to 2003 dealing with properties, processing, and applications in various industrial and biomedical fields.

3.15.1. Chitin and Chitosan

Processing Chitin and chitosan are natural resources waiting for a market. They were waste products of the crabbing and shrimp canning industry. The US Department of Commerce reported in 1973 that they were over 150,000 Mt of chitin produced as processing waste from shellfish, krill, clams, oysters, squid, and fungi. Commercially chitin and chitosan are of great importance owing to their relatively high percentage of nitrogen (6.89 per cent) compared to synthetically substituted cellulose. The crustacean shells mainly involves the removal of proteins and the dissolution of calcium carbonate that is present in crab shells in high concentrations.

The resulting chitin is deacetylated in 40 per cent sodium hydroxide at 120 °C for 1-3 h. This treatment produces 70 per cent deacetylated chitosan. The following four steps in chronological order of the process are needed to produce chitosan from crustacean shells:

- (i) De-proteinization,
- (ii) De-mineralization (Unpublished data, one of the authors, Pradeep Kumar Dutta investigated a new method of demineralization of crustacean shells and claimed better property than the existing process),
- (iii) De-colouration, and
- (iv) De-acetylation.



Figure 28 - Crustacean shells

Crustacean shells → Size reduction → Protein separation → (NaOH) → Washing
Demineralization (HCl) → Washing and Dewatering → Decolouration → Chitin → Deacetylation
(NaOH) → Washing and Dewatering → Chitosan

3.15.2. Properties of Chitin and Chitosan

Most of the naturally occurring polysaccharides e.g., cellulose, dextrin, pectin, alginic acid, agar, agarose, and carragenas are natural and acidic in nature, whereas chitin and chitosan are examples of highly basic polysaccharides. Their properties include solubility in various media, solution, viscosity, polyelectrolyte behavior, polyoxysalt formation, ability to form films, metal chelations, optical, and structural characteristics.

Although the $\beta(1\rightarrow4)$ -anhydroglucosidic bond of chitin is also present in cellulose the characteristic properties of chitin/chitosan are not shared by cellulose. Chitin is highly hydrophobic and is insoluble in water and most organic solvents. It is soluble in hexafluoroisopropanol, hexafluoroacetone, and chloroalcohols in conjunction with aqueous solutions of mineral acids and dimethylacetamide (DMAc) containing 5 per cent lithium chloride (LiCl).

Recently the dissolution of chitosan in N-methyl morpholine-N-oxide (NMMO)/H₂O has been reported by Dutta et al. The hydrolysis of chitin with concentrated acids under drastic conditions produces relatively the pure amino sugar, D-glucosamine. Depending on the extent of deacetylation, chitin contains 5 to 8 per cent (w/v) nitrogen, which is mostly in the form of primary aliphatic amino groups as found in chitosan. Chitosan undergoes the reactions typical of amines, of which N-acylation and Schiff reactions are the most important. Chitosan glucans are easily obtained under mild conditions but it is difficult to obtain cellulose glucans.

N-acylation with acid anhydrides or acyl halides introduces amido groups at the chitosan nitrogen. Acetic anhydride affords fully acetylated chitins. Linear aliphatic N-acyl groups higher than propionyl permit rapid acetylation of the hydroxyl groups in chitosan. Highly benzoylated chitin is soluble in benzyl alcohol, dimethyl sulphoxide (DMSO), formic acid, and dichloroacetic acid. The N-hexanoyl, N-decanoyl and N-dodecanoyl derivatives have been obtained in methanesulphonic acid.

Chitosan forms aldimines and ketimines with aldehydes and ketones, respectively, at room temperature. Reaction with ketoacids followed by reduction with sodium borohydride produces glucans carrying proteic and non-proteic amino acid groups. N-carboxy-methyl chitosan is obtained from glyoxylic acid. Examples of non-proteic amino acid glucans derived from chitosan are the N-carboxybenzyl chitosans obtained from o- and p-phthalaldehydic acids.

Chitosan and simple aldehydes produce N-alkyl chitosan upon hydrogenation. The presence of the more or less bulky substituent weakens the hydrogen bonds of chitosan; therefore, N-alkyl chitosans swell in water in spite of the hydrophobicity of alkyl chains. They retain the film forming property of chitosan.

Chitosan is more versatile in comparison to chitin due to the presence of amino groups at the C-2 positions (70).

3.15.3. Chemical Properties of Chitosan

The chemical properties of chitosan are as follows:

- Linear polyamine,
- Reactive amino groups,
- Reactive hydroxyl groups available,
- Chelates many transitional metal ions.

Biological Properties of Chitosan

Following are the biological properties of chitosan:

- Biocompatible - Natural polymer, - Biodegradable to normal body constituents, - Safe and non-toxic, (the research in chitinase is noteworthy in this respect).
- Binds to mammalian and microbial cells aggressively,
- Regenerative effect on connective tissue,
- Accelerates the formation of osteoblast responsible for bone formation,
- Hemostatic,
- Fungistatic,
- Spermicidal,
- Antitumor,
- Anticholesteremic,
- Accelerates bone formation,
- Central nervous system depressant,
- Immunoadjuvant.

3.15.4. Derivatives of Chitin and Chitosan

Chitosan may be readily derivatized by utilizing the reactivity of the primary amino group and the primary and secondary hydroxyl groups. Glycol chitin, a partially o-hydroxyethylated chitin was the first derivative of practical importance.

Derivatives of chitin may be classified into two categories; in each case, the N-acetyl groups are removed, and the exposed amino function then reacts either with acyl chlorides or anhydrides to give the group NHCOR or is modified by reductive amination to NHCH₂COOH of greatest potential importance are derivatives of both types formed by reaction with bior polyfunctional reagents, thus carrying sites for further chemical reaction.

In practice, such reactions are carried out on native chitin or on incompletely deacetylated chitin, chitosan, so that the resulting polymer contains three types of monomeric units. These polyampholytes are particularly effective in removing metal cations from dilute solutions.

Chitosan itself chelates metal ions, especially those of transition metals, and also finds application as a matrix for immobilization of enzymes. Special attention has been given to the chemical modification of chitin, since it has the greatest potential to be fully exploited. Reactions with pure chitin have been carried out mostly in the solid state owing to the lack of solubility in ordinary solvents. A 50 per cent deacetylated chitin has been found to be soluble in water. This water-soluble form of chitin is a useful starting material for its smooth modifications, through various reactions in solution phase. Some of the very recently reported chitosan derivatives are enumerated as follows:

(i) N-phthaloylation of Chitosan

Owing to its poor solubility in some limited organic solvents, it needs some chemical modifications. N-phthaloylation of chitosan was expected to be effective for solubilization since it affixes a bulky group to the rigid backbone and breaks hydrogen atoms on the amino groups to prevent hydrogen bonding. Fully deacetylated chitosan was treated with phthalic anhydride in DMF to give Nphthaloyl-chitosan. It was readily soluble in polar organic solvents. Further reactions had been carried out using this new derivative to improve the solubility of chitosan. Those are given below for better understanding.

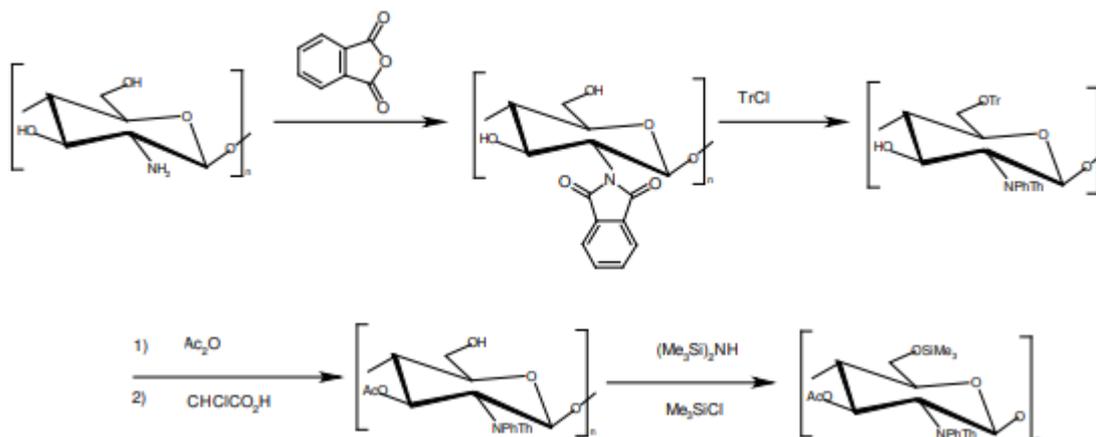


Figure 29 - N-phthaloylation of Chitosan

All these derivatives are soluble in common polar organic solvents.

(ii) Dendronized

Chitosan-sialic Acid Hybrids To improve water-solubility, Sashiwa et al. has successfully synthesized dendronized chitosan-sialic acid hybrids by using gallic acid as focal point and tri(ethylene glycol) as spacer arm. The water solubility of these novel derivatives was further improved by N-succinylation of the remaining amine functionality.

(iii) Methylthiocarbamoyl and Phenylthiocarbamoyl

Chitosans Recently, Baba et al. have synthesized methylthiocarbamoyl and phenylthiocarbamoyl chitosan derivatives to examine the selectivity toward metal ions from aqueous ammonium nitrate solution.

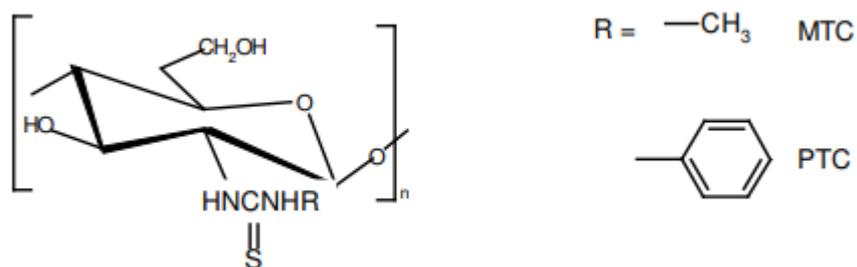


Figure 30 - Methylthiocarbamoyl and Phenylthiocarbamoyl

(iv) Lactic/glycolic Acid-chitosan Hydrogels

The synthesis of chitosan hydrogels was carried out by Qu et al. by direct grafting of D,L-lactic and/or glycolic acid onto chitosan in the absence of catalysts. They demonstrated that a stronger interaction existed between water and chitosan chains after grafting lactic and/or glycolic acid. The side chains could aggregate and form physical crosslinking, which results in pH-sensitive chitosan hydrogels. These hydrogels are considered potentially useful for biomedical applications such as, wound dressings and drug delivery systems, since both polyester side chains and chitosan are biocompatible and biodegradable.

(v) CdS Quantum dots (QDs)

Chitosan Biocomposite Derivatives with CdS QDs improved aqueous solubility and stability of chitosan. They also influenced the thermal decomposition of chitosan. In the presence of this thermal decomposition of chitosan was shifted to 50 oC. An efficient procedure for the preparation of CdS QDs chitosan biocomposite is achieved by mixing chitosan with Cd(Ac) and subsequently dissolving in 1 per cent HAc aqueous solution, followed by the treatment with CdS and thus smooth, flat, yellow CdS QDs chitosan composite films were obtained.

(vi) Chitosan-gadopentetic Acid Complex Nanoparticles for Cancer Therapy

The potential of gadolinium neutron capture therapy has been reported in the recent past. In 1999, Tokumitsu et al. have reported that chitosan-gadopentetic acid complex nanoparticles could be used for gadolinium neutron capture therapy (GdNCT). It is a cancer therapy that utilizes protons and neutrons and electrons emitted in vivo as a result of the nuclear neutron capture reaction with administered gadolinium-157, a non-radio element. Tokumitsu et al. have demonstrated that Gd-NCT using novel gadolinium-loaded nanoparticles are potentially highly suitable for intratumoral injection into solid tumor.

(vii) Nanocomposite from Natural Polysaccharide (Chitin/chitosan)

Although chitin and chitosan are useful biomass polymers, their applications are limited. An outstanding concept would bring a revolution by mixing natural polymers with manmade polymers (synthetic polymers). Institute for Marine Resource and Environment, Japan studied mechanochemical preparation of a novel composite under a dry and solid state. They

synthesized a new type of polysaccharide composite by ball-milling a polysaccharide with synthetic polymer.

The thermal behaviour and molecular motion of the synthetic polymer in the composite are entirely different from those of original one. These results suggest strong interactions between a polysaccharides and synthetic polymer and thus compatibilization of the polysaccharides and synthetic polymer. The authors' laboratory synthesized chitosan-poly(lactic acid) based nanocomposites under mild conditions for smart drug release (Unpublished results).

3.15.5. Applications of Chitin and Chitosan Fibers

Chitin and chitosan fibers find potential application in absorbable sutures and wound-dressing materials due to their ability to accelerate the wound healing. Chitin sutures are resistant to bile, urine, and pancreatic juice, which may degrade other absorbable sutures. Also, chitin and chitosan are also used in wastewater treatment as the heavy metal ions can be removed through chelation. Photography is another application area of chitosan due to its resistance to abrasion, its optical characteristics, and film-forming ability. Silver complexes can easily diffuse from one layer to another of a film because they are not significantly retained by chitosan. In the cosmetic industry, chitosan and its derivatives find wide applications in creams, lotions, nail lacquers, and the like.

3.15.6. Textile Applications of Chitin/Chitosan Fibers

- Sports: Uniforms of professional baseball players, wrist bands, underwear, slide pants, T-shirts, socks, sweat shirts, tennis socks, sweat bands, inside cloth of shoes
- Underwear: Infant, children, men, and women
- Ladies wear
- Baby clothes: Outerwear and blankets
- House interior
- Beddings: Ticking, bed cover, and pillow case
- Towels
- Nonwoven fabric: Dish towels and mask filters.

4. EXPERIMENTAL

4.1. Objective

In this experimental, to develop an antimicrobial and ecological Open-End yarns, we applied the steps which explained in previous parts of the study. The aim is, increase the usage of recycled cotton fibers in textile sector and adding antimicrobial properties to them. And also after producing the yarn and fabric samples, testing if suitable for use as antimicrobial clothing.

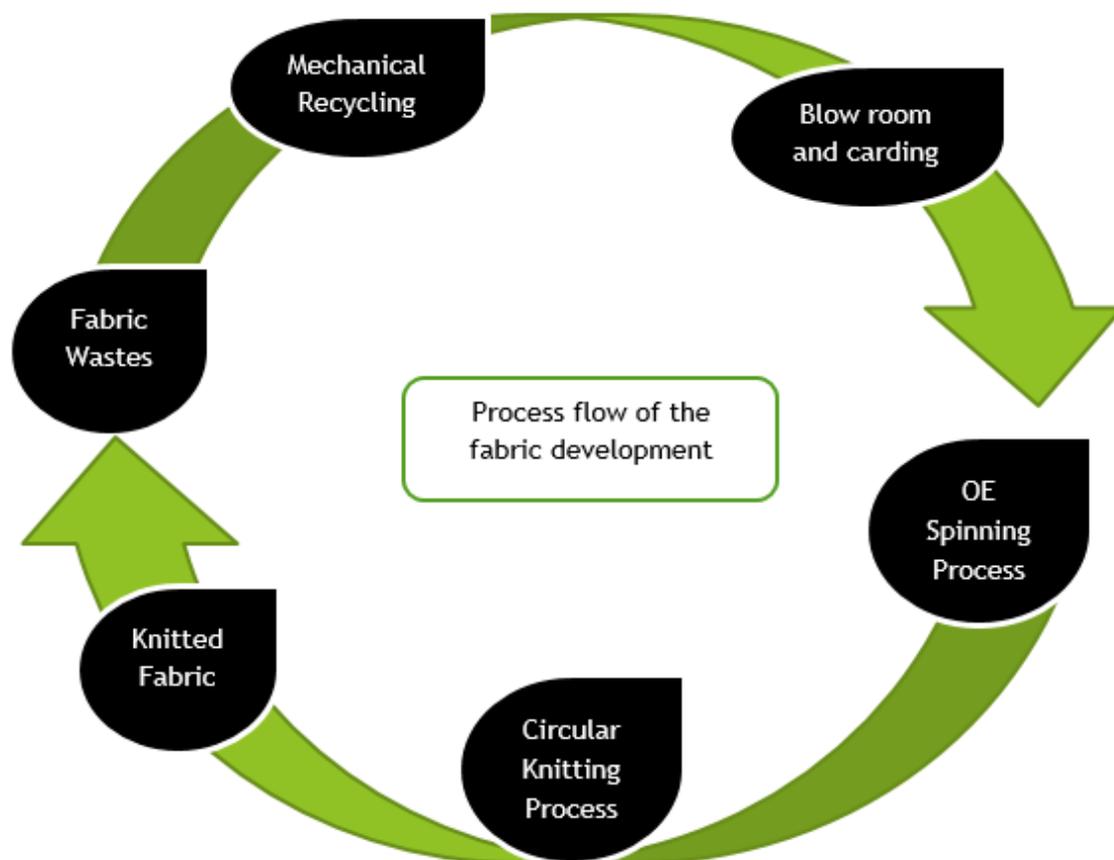


Figure 31- Process flow of the fabric development process

Our main raw material for the prototype production is cotton fiber. For clothing purpose yarns, producing from unused textile waste which comes from cutting departments of the apparel manufacturing companies. The companies which collect the textile waste classify the cutting clips by color and quality and the textile recycling companies receive these goods as ready for recycling.

4.2. Methodology

Materials:

- a) Recycled cotton fibers: Fiber length between 12-24mm and denier 1.1 to 1.6. (Cotton:3.675 g raw white and 400 g dark Bordeaux color)
- b) Chitosan Staple fibers: 38mm length and 1.5 deniers. (Chitosan fiber: 425 g)

Equipment:

- a) Textile Waste Recycling Machine: Recycled cotton fibers produced in Alcocertex S.L.U. (Alicante, Spain)
- b) Carding and Open-End yarn spinning machinery: Sample yarns produced in Hilosa S.A. (Girona, Spain)
- c) Yarn Twist counter.
- d) Precision Weighing Machine
- e) Machinery for yarn properties testing (Tenacity, Neps, Thin and Thick parts, elongation): For the test used Hilosa S.A. internal laboratory (Girona, Spain)
- f) Circular Knitting machine (socks sampling): Sample fabric produced in Uludag University (Bursa, Turkey)
- g) AATCC-147 test kit: Antimicrobial tests realized in an external laboratory (Spain).

4.3. Textile Waste Recycling

We obtained our recycled cotton fibers from Alcocertex S.L. which is situated in Alcocer de Planes (Alicante) and well experienced for yarn spinning sector and produce high quality shoddy for Open End yarn production use.

Raw Material Preparation Processes

To have fibers suitable for yarn spinning, recycling process need to be made with optimum adjusts, get longer fibers from the scraps and less powder and contamination. In textile recycling, cotton fibers becoming shorter than the virgin cotton fiber in the pulling process and also it can cause to have powder. Recycling steps which we applied for our experimental as in the continuation.

Opening Bales and cutting big scraps:

Textile scraps which comes from the clothing companies are sorted by color and quality. As seen in the photo for each production lot, **bales classified by color.**



Figure 32- Ready bales for recycling

First step for the recycling, is cutting the scraps to make suitable for the pulling and opening the textile scraps till fibers. Small pieces being forwarded to the mixing room after cutting.



Figure 33 - Feeding textile waste for cutting and transforming to little scraps.

Little scraps will be mixed in the rooms named “fresa” and allows to produce uniform colors at the end of the process. For each production lote, can blend up to **7.000kg of textile scraps for recycling.**



Figure 34 - Transferring the cutted scraps for blending.

Recycling machine has special parts and rolls for making smaller parts of scraps in the entrance and in the last parts of the machine opening the yarns till fibers. Also has some carding rolls which detects the big scraps escaped and drops them to re-pass from the beginning of the machine. With this machinery it is possible to produce recycled cotton fibers between 700 - 1200 kg materials per hour. **Velocity of the machine adjusted to 800 kg per hour for the sample.**



Figure 35 - Textile waste recycling machine.

As seen in the photos, in the entrance of the machine still visible textile scraps and also below unopened scraps to feed. And at the end of the process we see the finished product in fiber form. The next step is baling the fibers, and prepare for the transport. This material also used in our experimental and produced sample number 5.

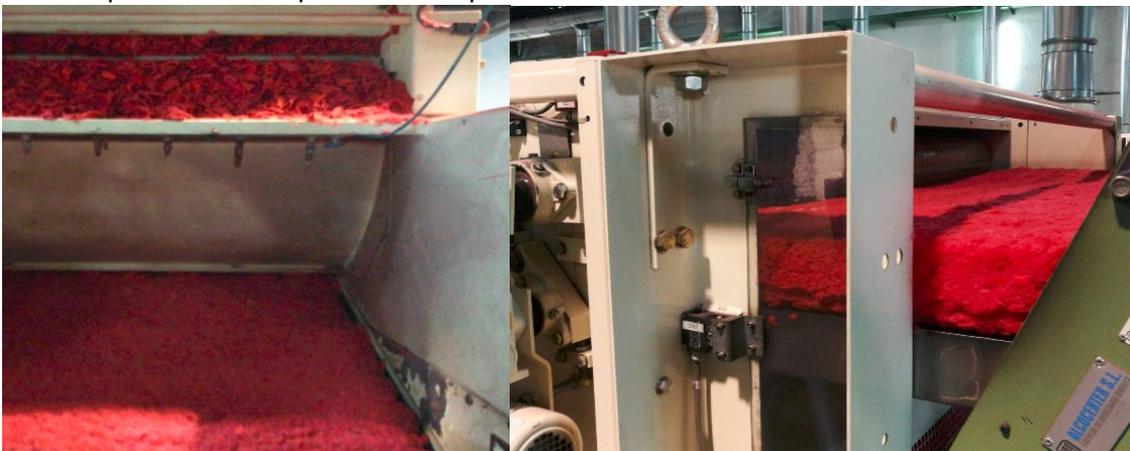


Figure 36 - Pulled textile waste and its transformation to the fiber.

Recycled fibers are called as shoddy. For our experimental used 100% cotton shoddies and 2 different material.

First shoddy sample: Raw White, produced from yarn wastes, undyed. This material can be dyed or bleached depend on the end uses.

Second shoddy sample: Dark Bordeaux, produced from colored cutting clips. It does not require to dye, already has color and we can say more environment friendly.

4.4. Open End Rotor Yarn Spinning

For our use, produced 5 different blends of recycled cotton fibers and chitosan fibers:

- 1- **2.5% Chitosan** and 97.5% Recycled cotton fiber (975gr Recycled cotton fibers, raw white and 25gr chitosan fibers of 38 mm)
- 2- **5% Chitosan** and 95% Recycled cotton fiber (950gr Recycled cotton fibers, raw white and 50gr chitosan fibers of 38 mm)
- 3- **10% Chitosan** and 90% Recycled cotton fiber (900gr Recycled cotton fibers, raw white and 100gr chitosan fibers of 38 mm)
- 4- **15% Chitosan** and 85% Recycled cotton fiber (850gr Recycled cotton fibers, raw white and 150gr chitosan fibers of 38 mm)
- 5- **20% Chitosan** and 80% Recycled cotton fiber (400gr Recycled cotton fibers, dark Bordeaux color and 100gr chitosan fibers of 38 mm)



Figure 37 - Used colors in our experimental: Raw white on the left and Dark Bordeaux color on the right.



Figure 38 - Chitosan staple fibers.



Figure 39 - Prepared samples in little amount.

Production of the yarn samples realized in Open End yarn spinning company named Hilados Olotoenses S.A. (Hilosa) which is situated in Les Preses (Girona) and produce eco-friendly yarns for upholstery productions, home textile and for socks.

In a recycled cotton yarn spinning mills, **production starts from blending and carding process**, by this way they do not need any machinery for opening bales and cleaning. Recycled cotton fibers comes as clean and ready for blending.

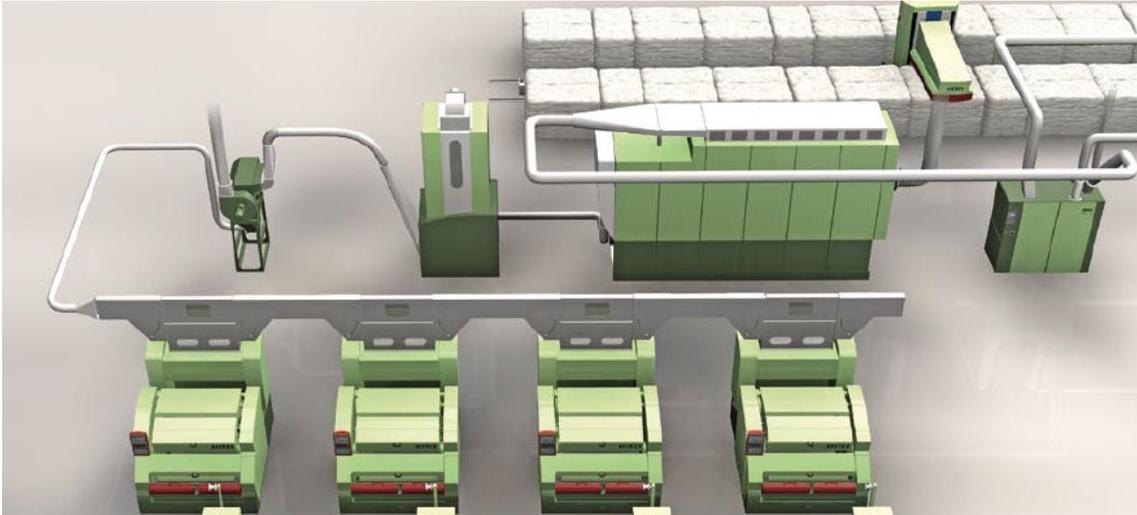


Figure 40 - Transferring the fibers to the carding machine. Basically we take the fibers from several bales and feeding to the carding machine as blended regularly.

All cleaning processes for yarn spinning preparation, will be passed when used recycled cotton. The process starts from feeding fibers to the carding machine.

A carding machine can process from 45kg to 220kg fibers per hour if the fibers are virgin. In our case, factories prefers to work between 80-120kg per hour, as the materials can contain unopened yarns or little fabric scraps. By **working with less velocities, we can have cleaner and more regular slivers** which we will use for spinning.



Figure 41 - Carding machine. Rieter C60

For our experimental, **velocity used in the carding machine was 100kg per hour.**

Sample	Cotton - grams	Chitosan - grams	Total - grams	Weight After Carding - grams	Wasted fibers %
1 – 2.5%	975	25	1000	860	14
2 – 5%	950	50	1000	880	12
3 – 10%	900	100	1000	875	12.5
4 – 15%	850	150	1000	890	11
5 – 20%	400	100	500	430	14
Avarage					12.7

Table 14 - Used fiber quantities and fiber loses.

Recycled cotton material contains some small scraps which is not opened during the recycling process and also contains yarns which is not transformed to fibers. This cause to have more waste in carding process. Also cotton powders are eliminated in carding, it effects to wasting in this process as well.

From the carding machine we obtain a **sliver with the count 144Ktex** and we pass them to the draw frame.

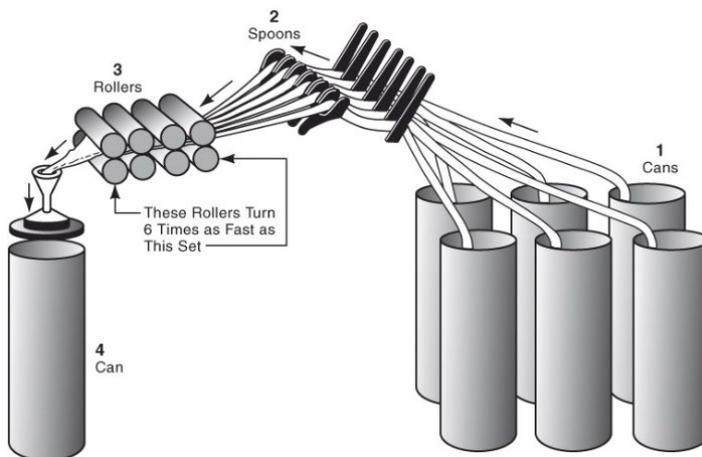


Figure 42 - Purpose of draw frame.

The sliver transferred from the filled can from the carding machine and passed from the rollers as shown in the figure.

In draw frame also used the same velocity as in **carding machine, it is 100kg/h.** By turning the down rollers 6 times faster than the up rollers and dividing the coarse sliver by 6 we obtain:
 Final sliver count = $144\text{Ktex} / 6 / 6 = 4\text{Ktex}$.

Finally our material is ready for the Open End yarn production and **final sliver count is 4Ktex.**



Figure 43 - Open End yarn spinning machine.

For our samples we produce **Nm7** count yarns (143tex).

Sliver count which comes to rotors **4000tex**, and the draw value:

$$\text{Draw} = 4000\text{tex} / 143\text{tex} = 27.97$$

To obtain the standard value of tpm (twist per meter) we adjusted the **tpm as 470**.

Rotor velocity = 40000rpm.

$$\text{Production velocity} = 40000\text{rpm} / 470\text{tpm} = 85.11 \text{ m/min}$$

Chitosan / Recycled Cotton					
Drawing Frame					
Sample (% Chitosan)	2.50%	5%	10%	15%	20%
Sliver from Carding	144 Ktex				
Sliver to Spinning	4 Ktex				
Draw - Carding to Spinning	36 times				
Nm7 in Tex	143 tex	143 tex	143 tex	143 tex	143 tex
Draw - Spinning to Yarn	28 times				

Table 15 - Drawing Frame datas

Sliver produced in the carding machine, blended and the count became 36 times finer sliver in draw frame by pulling, during the spinning process the sliver fed from the drawing frame converted to yarn by pulling 28 times faster in the rotors.



Figure 44 - Produced yarn samples.

Sample yarns produced from each fiber blending prepared previously as shown in the photo. Blendings of 2.5%, 5%, 10% and 15% chitosan contains made with raw white cotton which can be dyed if required, the last sample with 20% chitosan fiber contains blending produced with colored recycled cotton which does not require to make any finishing or dyeing process. In the continuation quality test results and obtained values are given:

Twist and Yarn Count Results:

Sample (% Chitosan)	Chitosan / Recycled Cotton				
	Twists per meter				
	2.5%	5%	10%	15%	20%
Analysis - 1	470	460	460	470	450
Analysis - 2	480	475	460	460	465
Analysis - 3	475	470	470	465	445
Analysis - 4	470	480	475	480	480
Analysis - 5	480	475	485	470	460
Average	475	472	470	469	460

Table 16 - Twist number test made in EPSA lab.

Spinning machine adjusted to give 470 twist per meter, and it is resulted as in the table above. Twist counting test realized in EPSA-UPV laboratory with the norm ASTM D1422.

Sample (% Chitosan)	Chitosan / Recycled Cotton				
	Nm Yarn Count				
	2.50%	5%	10%	15%	20%
Analysis - 1	7.09	7.29	6.75	7.25	6.81
Analysis - 2	7.08	7.28	6.74	7.29	6.77
Analysis - 3	7.05	7.28	6.78	7.27	6.79
Analysis - 4	7.07	7.27	6.77	7.28	6.78
Analysis - 5	7.06	7.28	6.76	7.26	6.80
Average	7.07	7.28	6.76	7.27	6.79

Table 17 - Yarn Counts of produced yarns.

Spinning machine adjusted to produce Nm7 yarns and the results with average are above.

Yarn Twist Factor:

As we already have the count and twist results for all of our yarn samples, the calculation of twist factor as in the continuation:

Metric twist factor: $\alpha m = \text{twist per meter} / \sqrt{Nm} \text{ (71)}$

Sample	TPM	Count Nm	Twist Factor
1 – 2.5%	475	7.07	178.6421
2 – 5%	472	7.28	174.9348
3 – 10%	470	6.76	180.7692
4 – 15%	469	7.27	173.9425
5 – 20%	460	6.79	176.5318
Average	469.2	7.034	176.9118

Table 18 - Twist factor calculation for the yarn samples.

In average the **twist factor is approximately 177.**

The twist factor is the tangent of the fiber alignment to axis. It gives us information for which purpose we can use the yarn.

The twist per meter of a yarn is dependent on the yarn count. A fine yarn requires more twist than a coarse yarn for the same application.

Tenacity of the yarn samples:

Chitosan / Recycled Cotton						
Tenacity (Cn/Tex) for 470 tpm						
Sample (% Chitosan)	0%	2.50%	5%	10%	15%	20%
Minimum	1000	-	-	-	-	-
Standart	1100	-	-	-	-	-
Maximum	1200	-	-	-	-	-
Analysis - 1	-	1120	1135	1145	1150	1165
Analysis - 2	-	1125	1145	1140	1160	1160
Analysis - 3	-	1130	1140	1150	1155	1155
Analysis - 4	-	1120	1130	1145	1150	1165
Analysis - 5	-	1115	1130	1140	1155	1165
Average	1100	1122	1136	1144	1154	1162

Table 19 - Tenacity values of the sample yarns.

For Nm7 cotton yarns, the tenacity values should be between 1000 – 1200 Cn/Tex, samples produced are in the range and **suitable for use** in fabric production.

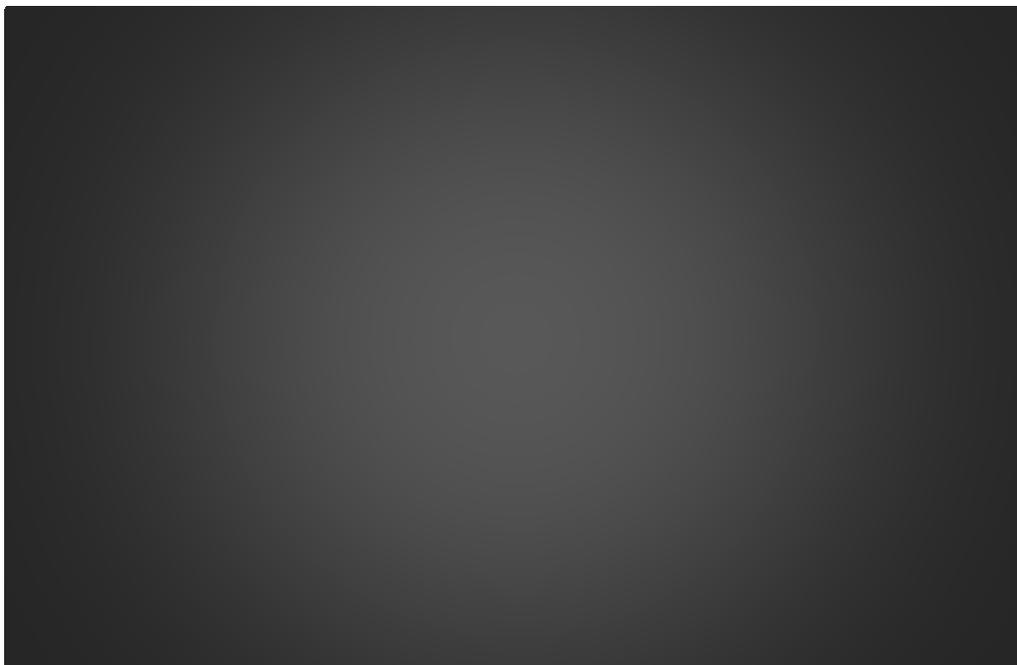


Figure 45 - Relation between tenacity and chitosan fiber concentration.

Recycled cotton fiber length used in the yarn samples are between 12-24mm and chitosan staple fibers length is 38mm. In this case the chitosan fibers define the yarn strength for being longer than recycled cotton fibers. Longer fibers make better joint than shorter. 5th sample which **contains 20% chitosan fiber has better tenacity** than the other samples for having more quantity of chitosan fibers.

Yarn Twist versus Yarn Count:

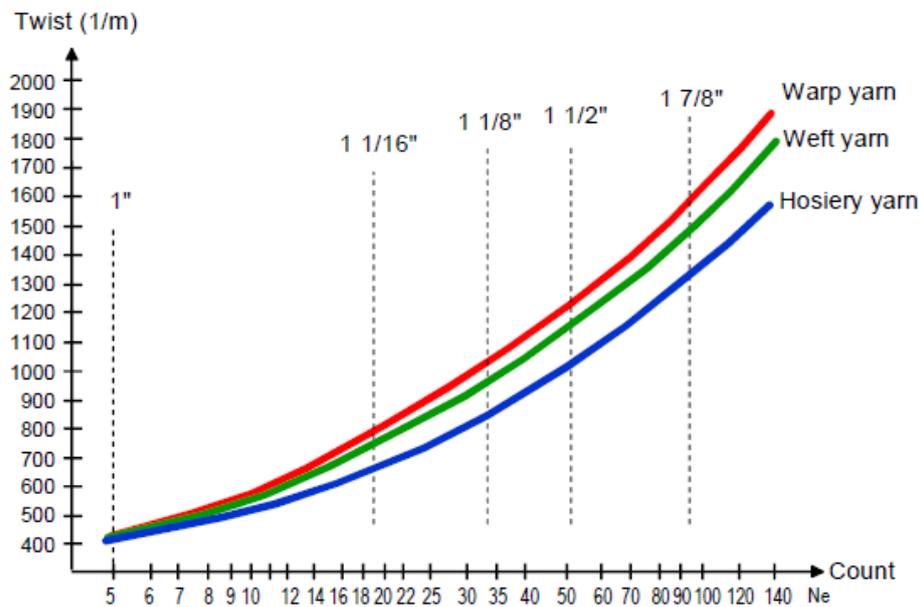


Figure 46 - Relation between yarn twist and yarn count. (71)

Softer yarns has less twist and for use in knitting, meanwhile harder yarns have more twist for weaving use.

Yarn Twist for a Specific End Use:

Twist Factor (α_m)	Application Range	Characteristics
76 - 118	Knitting Yarns	Soft Twist
90 - 130	Weft Yarns	Normal Twist
111 - 135	Warp yarns, Soft	Hard Twist
130 - 140	Warp yarns, Normal	Hard Twist
140 - 165	Warp yarns, Hard	Hard Twist
190 - 270	Crepe Yarns	Special Twist

Table 20 - Twist for various subsequent process. (71)

Twist factor value for our yarns in average is: 177 approximately.

We can consider that our yarns are suitable to use as warp yarns for having **hard twist** regarding to the above table.

Yarn Strenght versus Yarn Twist:

When the yarn twist increases, the yarn strength increases as well.

Our sample for high twist (**469 tpm for Nm7 yarn**), has high strength (**tenacity: 1114 cN/tex**) and suitable to use in weaving.

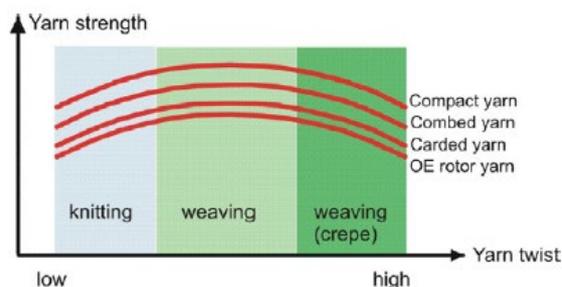


Figure 47 - Relation between yarn strength and yarn twist. (71)

Yarn Hairiness versus Yarn Twist:

With higher twist, we obtain more regular yarns with **less hairiness** on surface.

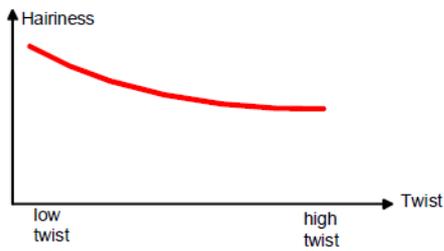


Figure 48 - Relation between yarn hairiness and yarn twist. (71)



Figure 49 - Hairiness photos of yarn samples (40x) Starting from left, by turn: 1, 2, 3, 4, 5.

As all our yarns have **similar twist numbers**, hairiness also very similar as seen in the photos.

Physical properties and imperfections:

Chitosan / Recycled Cotton			
Imperfections on the surface of the yarns			
	Thin Parts (-50%)	Thick Parts (+50%)	Neps
Minimum	0	5	10
Standart	5	75	50
Maximum	20	150	92
1 – 2.5%	8	112	88
2 – 5%	9	105	98
3 – 10%	11	124	79
4 – 15%	12	120	87
5 – 20%	14	115	89
Avarage	10.8	115.2	88.2

Table 21 – Imperfection results of the yarns produced from Hilosa.

As known, on the yarn surface we can see irregularity as thin and thick parts or neps. In Open-End yarn it is more usual. We can consider that the agglomeration of the entangled fiber area (neps) are normal and the thin/thick areas also.



Figure 50 - Shown thin/thick parts and neps. Samples starting from left by turn: 1, 2, 3, 4, 5.

Thin Parts: Higher numbers of this test indicated us the surface of the yarn is not very regular. Acceptable values for this test are between 0 – 20 and the normal yarn can have 5 thin parts per meter. Any of our yarns has this value between 0 – 5, average value of our yarns is 11 thin parts per meter. When a yarn has more thin parts than expected, it may result by braking the yarns in fabric production.

Thick Parts: It is similar to the previous test, in this case we count the thick parts and see the yarn surface irregularity. For this test the thick part per meter range is from 5 to 150 and the standard is 75 thick parts per meter. In this test also we have values higher than standard value but we are in the range. Working with recycling fibers in Open End spinning machines may result to have more thick parts and irregularities cause of different fiber lengths of recycled cotton fibers.

Neps: For our sample yarns (Nm1/7) the neps number are from 10 to 92 per meter and the optimum is 50 neps per meter. All of our yarn samples has the neps number in the maximum limit. During the yarn production, agglomeration of the entangled fiber cause for the neps and it seen usual in yarn which produced from recycled cotton.

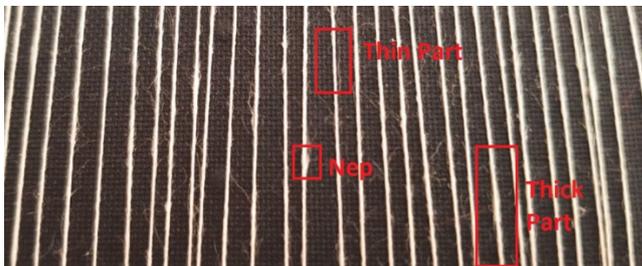


Figure 51 - How seen thick/thin parts and neps.

4.5. Circular Knitting with Socks Producing Machine

The knitting machine used is for sampling, which does not produce as final product but the aim is produce a tube of fabric for socks production to make antimicrobial tests subsequently.

Tubular fabrics produced in the textile laboratory of Uludag University (Bursa, Turkey)



Figure 52 - Tubular knitting fabrics produced with the 3rd yarn sample. Figure 53 - Sample sock knitting machine.

With the sampling machine used the velocity as 1 meter per minute and not faced any yarn breakage. Produced yarns have sufficient strength for the fabric production.

4.6. Summary of Physical Tests and Evaluations

The collected cutting waste from the apparel manufacturing unit was shredded into fibers and spun back into yarn and finally the knitted fabrics were developed using socks knitting machine. The developed yarns were analyzed for their suitability as an apparel fabric.

The yarn properties of normal cotton and recycled cotton yarns are provided in Table 17. From the result it can be seen that the imperfections are in acceptable ranges. The strength of the recycled yarn also in the range and suitable for the fabric production.

Thanks to previous researches and actual sector knowledges, we had been able to reach the expected results in our experimental. Practically we produced our recycled cotton fibers and by blending with chitosan fibers, obtained yarns to use in fabric production. However the produced yarns are used in knitting fabric in this experimental, it is also suitable for weaving process.

Yarn Count, Twist and Twist Factor: We produced yarns with count Nm7, and the twist number per meter: **470 tpm**. Twist number applied to the yarn makes it usable for weaving process called **hard twist yarn**.

Physical properties and values of our sample yarns like thin/thick parts, neps, elongation, tenacity are all in the **expected range** and shows us that is suitable for the fabric production. For each of five samples produced we have similar results.

Thin Parts: Higher numbers of this test indicated us the surface of the yarn is not very regular. Acceptable values for this test are between 0 – 20 and the normal yarn can have 5 thin parts per meter. Any of our yarns has this value between 0 – 5, **average value of our yarns is 11 thin parts** per meter. It has good results to consider **regular yarn**. When a yarn has more thin parts than expected, it may result by breaking the yarns in fabric production.

Thick Parts: It is similar to the previous test, in this case we count the thick parts and see the yarn surface irregularity. For this test the thick part per meter range is from 5 to 150 and the standard is 75 thick parts per meter. In this test also we have values higher than standard value but with **115 thick parts per meter we are in the range**. Working with recycling fibers in Open End spinning machines may result to have more thick parts and irregularities cause of different fiber lengths of recycled cotton fibers.

Neps: For our sample yarns (Nm7) the neps number are from 10 to 92 per meter and the optimum is 50 neps per meter. All of our yarn samples has the neps number in the maximum limit. **With 88 neps per meter we are in the range**. During the yarn production, agglomeration of the entangled fiber cause for the neps and it seen usual in yarn which produced from recycled cotton.

Tenacity: For our yarn, the acceptable tenacity values are between 1000 – 1200 Cn/Tex. All the result from our five samples are in the range and we can consider that our yarns has enough strength to be used in fabric production. **The yarn sample number 5 which contains 20% chitosan fibers has better tenacity**. Rest of the fibers also have acceptable value of tenacity.

4.6.1. Anti-microbial Evaluation

On our fabrics produces from developed yarns we applied the anti-microbial test AATCC-147. As determined in the Table 12, we searched the antimicrobial efficacy on five samples.

Efficacy of Antimicrobial Properties	Values for Antimicrobial Efficacy A
Insufficient	$A \leq 2$
Significant	$2 \leq A \leq 3$
Strong	$A \geq 3$

Table 22 - Efficacy of antibacterial properties according to AATCC147



Figure 54 - AATCC Kit

The first fabric sample produced with the yarn which contains 2.5% Chitosan fibers give the result as 2.9 regarding to the analysis made in an external laboratory. The minimum chitosan fiber contains yarns has significant antibacterial properties which means the other developed chitosan contains yarns (5%, 10%, 15% and 20%) has strong antimicrobial effects.

Sample Chitosan %	Time 0 hour	Time 24 hours	Growth Reduction %	Efficacy of antimicrobial properties	Values for antimicrobial efficacy
0%	None	None	None	None	None
1 – 2.5%	160000	<4800	97	Significant	2.9
2 – 5%	160000	<20	99.99	Strong	>3
3 – 10%	160000	<20	99.99	Strong	>3
4 – 15%	160000	<20	99.99	Strong	>3
5 – 20%	160000	<20	99.99	Strong	>3
Microorganism:				Staphylococcus aureus	

Table 23 - Antimicrobial test results and efficacy

Our first fabric sample produced with 2.5% Chitosan blended cotton yarns has value 2.9 where the maximum value can be 3 for antimicrobial tests. And the second fabric sample which produced with 5% Chitosan blended cotton yarns resulted with the maximum value.

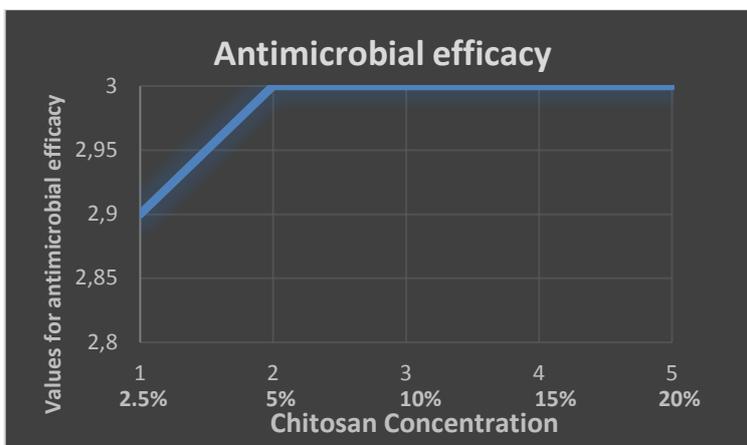


Figure 55 - Antimicrobial efficacy graphic

Third, fourth and fifth samples give better results for containing more chitosan fibers but as we already reached the strong antimicrobial properties with the second sample which contains **5% chitosan fiber resulted with optimum values.**

5. CONCLUSIONS

This study started with the idea of developing a new yarn which produced from recycled cotton fibers to be more ecological and chitosan staple fiber to have antimicrobial properties. Our yarns produced with open-end spinning method as these yarns have uses in many field of the textile sector.

Achieved Targets:

- **Antimicrobial value added** yarn produced by using chitosan fibers and resulted with strong efficacy for 5% chitosan concentration yarns.
- Produced recycled cotton fibers and chitosan fibers blended **yarns has enough strength** to use in regular textile fabric production.
- Acceptable thin/thick area and neps numbers on the yarn surface to consider **regular quality yarn**.
- This yarn is fit to **use for knitting** (with less twist), **weft yarn** (with medium twist) and **warp yarn** (with hard twist).
- The sample used in the experimental which contains 20% chitosan fiber, blended with colored recycled cotton fibers, achieved to **produce colored yarns without using chemicals and dyes**.
- Found **more possibilities to use recycled cotton** in the textile industry.

It can become commonly used materials in very near future for the properties and solutions for the pollutions. As we are able to give these properties to the yarns, it can be used in every part of textile industry.

In this research, we studied how to reuse the materials once produced and became a waste. Reuse allows us to keep the environment cleaner and save many production processes and save resources. We call "raw material" to the textile scraps which called "waste" in the past, and we are adding important values to them and preparing them to use in our common life.

The important issue is being able to produce ecological yarns at the same time which has antimicrobial properties. Giving more importance in this field and use them in our daily life.

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