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SUSTAINABILITY APPROACHES IN DENIM PRODUCTS AND PRODUCTION PROCESSES

DENİM ÜRÜNLERİNDE VE ÜRETİM SÜREÇLERİNDE SÜRDÜRÜLEBİLİRLİK YAKLAŞIMLARI

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SUSTAINABILITY APPROACHES IN DENIM PRODUCTS AND PRODUCTION PROCESSES

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ABSTRACT: Sustainability in denim refers to the practices implemented to reduce the environmental, economic and social impacts of the denim production process and these practices are divided into two as product and production process. Sustainable denim product practices include various approaches such as using environmentally friendly, organic materials and recycled denim. In the sustainable production process, there are more sustainable alternatives such as desizing with amylase enzyme, mercerization with the best available techniques, bleaching with enzyme, ozone and laser technologies, washing with natural resources and water reduction technologies. This study aims to explain the sustainable product and production process that can reduce waste, water and energy consumption, using environmentally friendly raw materials, recycling and reuse.

Keywords: Sustainable, denim production, recycled denim, denim fading, denim washing

DENİM ÜRÜNLERİNDE VE ÜRETİM SÜREÇLERİNDE SÜRDÜRÜLEBİLİRLİK YAKLAŞIMLARI

ÖZ*:* Denimde sürdürülebilirlik, denim üretim sürecinin çevresel, ekonomik ve sosyal etkilerini azaltmak için uygulanan uygulamaları ifade eder ve bu uygulamalar ürün ve üretim süreci olarak ikiye ayrılmaktadır. Sürdürülebilir denim ürün uygulamaları, çevre dostu, organik malzemeler ve geri dönüştürülmüş denim kullanmak gibi çeşitli yaklaşımları içermektedir. Sürdürülebilir üretim sürecinde amilaz enzimi ile haşıl sökme, mevcut en iyi tekniklerle merserizasyon, enzim, ozon ve lazer teknolojileri ile ağartma, doğal kaynaklarla yıkama ve su indirgeme teknolojileri gibi daha sürdürülebilir alternatifler bulunmaktadır. Bu çalışma, atık, su ve enerji tüketimini azaltabilecek, çevre dostu hammaddeler kullanarak, geri dönüşüm ve yeniden kullanıma sunabilecek sürdürülebilir ürün ve üretim sürecini açıklamayı amaçlamaktadır.

Anahtar Kelimeler: Sürdürülebilirlik, denim üretimi, geri dönüştürülmüş denim, denim ağartma, denim yıkama

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1. INTRODUCTION

Sustainability, which means continuity, is based on the principle of utilizing renewable resources by meeting human needs without harming nature or with minimal harm. Sustainability creates a healthy ecosystem by aiming for the continuity of natural and economic resources and the progress of humanity. Rapidly increasing human population, non-renewable energy use with the effect of developing technology, unconscious use of limited natural resources and increasing environmental pollution are among the important factors that emphasize the necessity of the emergence of sustainability. Sustainability involves recognizing the interconnectedness of economic, social, and environmental systems, and working to address the challenges that arise when these systems come into conflict. It requires considering the full lifecycle of products and services, from production and consumption to disposal and recycling, and striving to minimize negative impacts on people and the planet.

Sustainability in the denim industry refers to the environmentally and socially responsible production of denim garments, which minimizes negative impacts and maximizes positive contributions to society and the planet. While evaluating the effects of denim production on the environment, society and economy, all activities related to denim production such as raw materials, production, transportation, use and disposal should be evaluated, and all factors should be considered. These activities are included waste, water, and energy consumption, using eco-friendly raw materials, improving worker conditions and labour practices, and recycling and repurposing.

In this study, sustainability approaches that are frequently applied in terms of raw materials and production in the denim sector are examined. Firstly, the three main components of sustainability, namely environment, economy and social, are discussed. Then, the denim production process, eco-friendly denim and recycled denim products used in denim production and sustainability practices applied in dyeing, desizing, mercerization, fading and washing processes are explained. In order to reduce the environmental, economic and social impacts of the denim industry, sustainability practices are an important issue that should not be ignored.

2. SUSTAINABILITY

The concept of sustainability that emerged from forestry means never harvesting more than a newly growing forest produces. It was formed with the belief of protecting natural resources, traditional beliefs from our ancestors and concern for the future [1]. However, sustainability means more than forest protection rules. Sustainability means not using more resources than can be reproduced in the same period [2].

In its most basic form, sustainability means the capacity to be permanent. For something to be sustainable, it must be used for a long time. It is based on the principle of transferring the world we live into the next generations without harming them or with the least damage. It is to reconstruct the waste material, turn it into a product, and ensure its long-term use. Sustainability, one of the new elements of the scientific revolution, is a concept aimed at ensuring the continuity of natural and economic resources and the progress of humanity [3]. New technologies bring side effects as well as advantages. Sustainable development is a social task and is associated with the use of technology. In the absence of technological advances, societies can collapse. It is necessary to maintain the balance between technology and sustainability in order to develop societies. Therefore, in order to comply with the principle of sustainable technology, the concepts of “human”, “profit” and “planet” should be given priority [4].

The understanding that environmental pollution, especially encountered in industrialized regions of the world, began to threaten our future, gained an international character with the "United Nations Human Environment Declaration" published in Stockholm in 1972 for the first time. At the conference, attention was drawn to the carrying capacity of the environment, the use of resources, the main problems created by economic and social developments, and the foundations of the idea of sustainability were revealed [5]. The World Commission on Environment and Development, also known as the Brundtland Commission, in 1987, reconsidered sustainable development as the broad political vision. Sustainability has been defined as the viability of natural resources and ecosystems over time and the preservation of human living standards and economic growth [6]. The term sustainability was later discussed extensively at the United Nations Conference on Environment and Development (UNCED) held in Rio in 1992. At the Rio conference, sustainable development goals were set on environmental issues on climate change, biodiversity, and desertification [7]. In 2002, the World Sustainable Development Summit was held in Johannesburg. As a result of the summit, two documents, “Johannesburg Declaration for Sustainable Development” and “Johannesburg Implementation Plan” were presented. As a result of the summit, the objectives of the “Implementation Plan” such as eradicating poverty, changing unsustainable production and consumption patterns and sustainable development in the globalizing world were revealed [8].

2.1. Environmental Approaches

Problems such as global warming, depletion of natural resources, climate change, and depletion of the ozone layer, acid rain and air pollution are increasing day by day. These problems may affect many areas, especially human health, and become unavoidable problems for future generations in the end. Solution methods that can be applied in this sense; It is seen as the use of renewable energy and substances, the prevention of air pollution and ozone depletion, and the use of sustainable resources. With environmental sustainability approaches, it is aimed to use the air, water, and land resources of people in an economical way. Increasing environmental pollution as a result of production and consumption brought about by overconsumption with population growth causes depletion and destruction of natural resources.

Environmental sustainability is a universal issue that many countries should consider. The balance between production and consumption activities that will be needed for all countries differs. Some countries need to focus more on controlling pollution, while others need more to reduce harvest rates of renewable sources to regeneration rates or reduce per capita consumption [9]. For example, in countries with intensive agricultural production, it is possible to encounter problems such as deterioration of soil health and land when environmental sustainability is not taken into account. In addition, there are problems such as the extinction of large whales and the decline of many fish and tropical timber stocks below harvestable levels. In this sense, it will be a solution for OECD (Organisation for Economic Co-operation and Development) countries to take action and lead the way compared to developing countries. Some measures can be taken, such as implementing environmental sustainability policies and reducing excessive consumption and waste [10].

Within the scope of the environmental sustainability principle, industrial ecology and green chemistry applications such as wastewater management, energy management, and reduction of CO2 emissions are included. In this sense, applications that can significantly reduce the high energy consumed in the cement production process and environmental impacts [11], the use of wastewater streams as a potentially valuable resource [12], applications such as industrial monitoring and control systems aimed at reducing energy consumption in building energy management systems [13] can be given.

The most important issue to be considered in sustainability practices is the carbon footprint. Carbon footprint (CFP) is defined as the measure of the damage caused by human activities to the environment in terms of the amount of greenhouse gas produced and measured in units of carbon dioxide [14]. CFP originates from the global warming potential (GWP) and was first included in the scientific literature by Høgevold in 2003 [15]. The effects of climate change cause carbon footprints to be seen widely. CFP carries risks of chemical pollution or depletion of natural resources [16]. For example, for a T-shirt in the textile industry, the CFP calculation covers the time from cotton planting to the final finishing of the T-shirt. [17]. Another concept, water footprint (WF), is defined as the total volume of fresh water used, consumed, and polluted. WF is measured by calculating the volumes of polluted water per unit time or functional unit during evaporation, incorporation into the product [18]. Cotton fiber is one of the most used fibers to create fabrics in the world textile industry. In the production of cotton fabrics, a water footprint is created for the agricultural process, such as the production and harvesting of cotton, and for the industrial process, such as turning the fibers into fabrics. Cotton's WF consists of three water footprints: green, blue, and gray. Evaporation of infiltrated rainwater represents the green WF, while surface or groundwater extracted for irrigation represents the blue water footprint [19]. Gray WF identifies copper and silver contaminants. The woven fabric sizing process has the greatest variation in high gray WF contaminants, followed by stock and yarn processing and simple knit fabric processes [20].

Life cycle assessment (LCA) is often used to assess the environmental impacts of a product. LCA is a multi-step assessment method for calculating environmental impacts, such as CFP, over the life of a product [21]. LCA is defined by ISO 14040 as "compilation of life cycle assessment (LCA) principles, framework and environmental impacts" [22].

2.2. Economical Approaches

Developing countries need land for food, rivers for water, and forests for fuel. For this reason, the consumption of natural resources and environmental destruction are increasing. Economic growth should be less energy consuming and environmentally friendly potential for environmental development. A balance must be struck between economic growth and environmental destruction. The gains of less developed countries compared to developed countries are decreasing day by day. In this sense, industrialized countries should develop new policies [23]. For countries to provide economic sustainability approaches correctly, cost and performance factors should be considered. Production costs and life cycle costs are considered for economic evaluation [21]. It is important to intervene in the circular economy and the textile industry while making this assessment. The circular economy (CE) business model has a structure that aims to prevent resource depletion and close the energy and material cycles. For the correct implementation of the CE business model, an organizational transformation is necessary to reveal the current cyclical state of the supply chain and identify challenges and opportunities [24].

The textile sector has an important place in economic development with factors such as industrial production and employment. For this reason, sustainable efforts are made at every stage in the textile industry, from fiber production to the production of textile products, and are encouraged to make higher profits. Within the scope of economic sustainability, an economic sustainability radar such as partnership or cooperation, profitability, added value, new market position and competitiveness development and long-term business development is created [25-27]. Achieving a sustainable economy in the textile sector can be achieved by achieving high profitability with minimal environmental damage and resource use. For this reason, determining factors such as management of intangible assets of enterprises, energy and raw material cycle, market competitiveness and country policies should be taken into consideration.

2.3. Social Approaches

Social sustainability focuses on meeting the basic needs of individuals as a complement to environmental and economic sustainability. It includes equality, welfare and balance between socio-cultural groups and legal entities [28]. For example, factors such as social homogeneity, fair incomes, equal access of people to goods, services and employment ensure social sustainability and holistic development in a society [29]. Creating an environment that is compatible with fair social, economic, and environmental conditions among people, regardless of race, religion, language, gender, culture, or socio-economic status, constitutes the vision of social sustainability. This idea is capable of creating radical new form and value in the future [30]. One of the sectors with the highest human employment is the textile sector. Social sustainability in the textile sector should be developed through improvements in the quality of life such as good working conditions in the business environment, fair wages, raw material production that does not harm human health, equality between men and women, and appropriate working hours. There is no doubt that social sustainability will support stability in these areas, people working in harmony and welfare as well as economic development.

3. DENIM INDUSTRIES AND DENIM FABRIC PRODUCTION

Denim is a type of cotton fabric in which the weft thread goes under two or more warp threads. The most widely known type of denim is the indigo colored twill weave, in which the twist yarn is left blue and the weft yarn white [31]. Generally, denim fabrics are 3/1 twill cotton fabric and having weights of 14½ ounces per square yard. The most frequently used denim fabric structures are 2/1 and 3/1 different combination twill structures (Figure 1.) [32]. The name ‘denim’ is thought to have originated from the French serge de Nimes. Denim firstly was a durability fabric especially in the manufacture of overalls and trousers for hard labour but now denim products are used in extremely popular for leisure wear [33].

The denim industry, which constitutes a significant percentage of the textile industry, maintains its superiority in imports and exports in the world clothing market. The USA and the European Union (EU), as the top developed countries, import most of the denim textile and apparel products. Mexico, the most important supplier of denim pants, is followed by China and Bangladesh. These three countries account for more than 66% of raw denim imported into the USA [33]. Denim consumers worldwide differ between Europe, the USA and Asia. While European consumers demand high-priced fashion denim, American consumers are generally willing to pay less than international consumers [34]. Consumer preferences are a factor that differs according to geography, culture, and demographic structures.

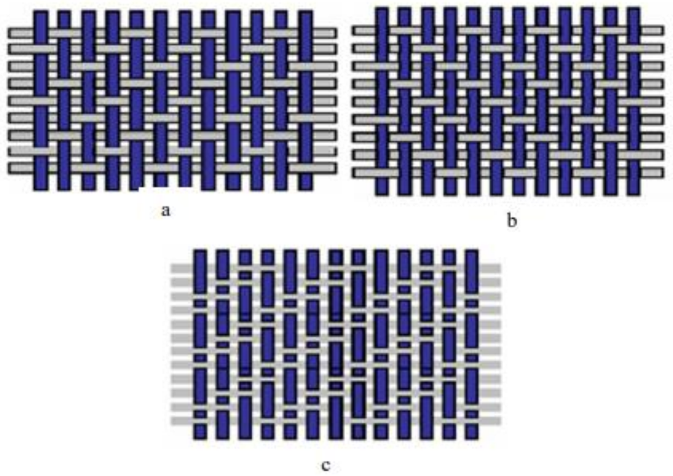

Figure 1. Common weaving construction types used at denim fabric types a) 2/1 Z Twill, b) 2/1 S Twill, c) 2/2 Z Twill [32]

Denim fabrics have some general features. The warp thread of denim fabrics is cotton thread dyed with indigo dye or sulphur dyes, and the weft thread is white cotton thread. The front and back faces are different due to the fabric weave. White weft threads are prominent on the reverse, and dyed warp threads are evident on the front. Warp yarn is thinner and more tightly twisted than weft yarn. The pH value of denim fabrics should be between 8-10. Light fastness is expected to be 4, sweat fastness to 5, friction fastness to maximum 3 for dyestuffs [35].

The process flow chart of denim fabric production, which includes spinning, warp preparation, fabric production and finishing processes, is shown in figure 2. The first stage in denim production starts with spinning the yarn in either a ring spinning or rotor spinning system. The conversion from fiber to yarn consists of various processes such as opening and cleaning, carding, drawing, roving, and spinning. In second step, warp yarns are dyed by the loop dyeing, rope dyeing or slash dyeing method with indigo. Synthetic indigo dyestuff is widely used in denim dyeing as it imparts the characteristic natural indigo blue color to denim [36] In loop dyeing, the yarns are dipped several times in the same bath. The second method is slash dyeing method. In the sizing procedure with slasher dyeing, 12 to 16 tension-controlled warp beams consisting of 350 to 400 threads of 50.000 m length are placed in front of the Slasher line. The Slasher line provides continuous dyeing, drying, sizing and warping in a single process cycle [37]. Third method is the rope dyeing technique, the rope wrapping process is done first in this. Approximately 350-400 threads are combined and made into ropes. At this point, it is important that the yarn tensions in the rope are equal or very close to each other. Around 12-14 ropes are passed through the dyeing machine. After dyeing, the ropes are dried in the drying cylinders, and the worker beam is prepared in the last step [38].

In denim production, after dyeing, sizing is used to increase the strength of the yarns during weaving. Indigo sizing is preferred for easy dissolution in hot water for washing after denim weaving [37].

In another step is the weaving process, which has shuttle- less, shuttle weaving and air system weaving machines [31, 37]. For the finishing processes, denim fabric goes through a singeing, brushing, washing, and drying. With these processes, it is aimed to provide the fabric with a smoother, non-rolling, soft, shiny, and slippery appearance. After the finishing processes, the denim fabric is inspected for defects such as uneven dyeing, bleaching and dyeing defects, oil stains, patches. Thus, denim fabrics could be categorized according to the quality. Last step of denim production is garment manufacturing, which have several operations such as pattern making, spreading, cutting, sewing, pressing, inspecting, and packaging [31, 38].

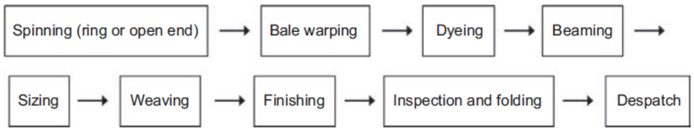

Figure 2. Warp yarn production flowchart of denim fabric [39]

Denim washing is an aesthetic finishing applied to the fabric to improve and improve the softness and comfort of the fabric. Chemicals and stones are used largely to achieve the softening and discoloration effects of denim garment washing [36]. There are two types of washing processes: dry and wet processes. Dry processes include eight different mechanical processes: scarping, sandblasting, manual damage, tagging, laser, resin, ironing-creases and flat press, print. Wet treatments are listed as desizing, stonewash, enzyme wash, bleaching, tinting – overdyeing, softening, rinse, rubber balls. While the aim in dry processes is abrasion, the purpose in wet processes is to give an appearance effect [37].

4. SUSTAINABLE DENIM PRODUCT APPLICATIONS

Sustainability can be evaluated based on a product/process, project, sector, and country. When this evaluation is examined in general terms, we come across as life-cycle evaluation or life-cycle thinking. Life cycle assessment (LCA) is a scientific method or tool for identifying, measuring, and evaluating all environmental impacts of a product, service, or activity throughout its entire life cycle [21]. It is used effectively to calculate the effects of the product, service, or activity on the environment, to identify the problematic points of production and to get down to the source of the problems. LCA, which also deals with the relationships between companies, suppliers, and customers, thus provides a total analysis of the environmental effects of a product from the cradle to the grave.

LCA for the denim industry can be divided into four phases. The first stage includes defining the objectives of the study and defining the denim product. The second stage is the collection and processing of data from all processes of the product life cycle, from the acquisition of raw materials used in denim to the development of the final product. At this stage, energy, raw material requirements, environmental emissions and discharges related to the denim product can be calculated and presented. This data can be used to calculate discharge from all processes of the product lifecycle. The third phase is called the "impact assessment phase", where the collected data is translated into its effects on human health, ecological health, and resource consumption. The final stage of the LCA process can be termed 'recommendations' based on the analysis of the impact assessment results [40]. LCA is a system that analyzes the entire process, from raw material to final product. Thanks to the special software developed for this system, many environmental effects can be demonstrated with numerical data. It has a very important place in the denim industry, which is one of the textile production areas where waste management and resource consumption are the highest.

It is a progression in the denim production cycle, starting with natural resources cultivation and extraction and continuing with consumer use and care. In this progress, reuse and recycling of denim products is an approach that completes the cycle. In this section, the raw materials of sustainable denim products will be examined under three main headings: eco-friendly denim, recycled denim and eco labels for denim production (Figure 3.).

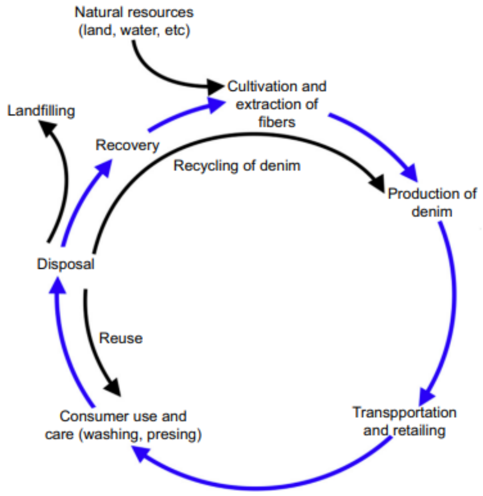

Figure 3. Phases of a product's life cycle (for denim). [40]

4.1. Eco-Friendly Materials in Denim Fabrics

Organic cotton, alternative natural fibers or recycle fibers materials are used to reducing the environmental effect of denim production. The use of these eco-friendly materials helps to create more environmentally responsible denim products that are healthier for both people and the planet.

One of the most used fibers is cotton in the textile industry. Preparing cotton raw material 1 kg organic cotton requires 7 to 29 tons of water. Cotton is the most toxic crop in the world [41]. Cotton uses more than 25% of all insecticides and 12% of all pesticides in the world. These insecticides are known as the most toxic chemicals in the world. Pesticide exposure poses many health risks, including birth defects, reproductive disorders, and immune system damage [40]. One of the most important property is tensile strength for denim fabrics. The tensile strength of denim fabrics must be maintained in the final product because the strength has a very important effect on the service life of the garment [42]. The fuzzy logic model was evaluated by Sarkar et al. [42] and the average relative error for tensile strength in warp and weft directions was found to be 2.82 and 3.92, respectively. In addition, the fixation coefficient for the tensile strengths in both the warp and weft directions was determined as 0.99. In the research, it was concluded that the tensile strength of 10 denim fabrics was compatible with the tensile strength found by fuzzy logic. With this model, it was possible to predict the tensile strength of denim clothes washed with bleach. Additionally, it was concluded that the environmental footprint of the applied model was positive in terms of material and process. Tarhan and Sarıışık (2009) [43] in their study, seen that fading methods decreased tensile strength and weight values, and color abrasion values of the fabrics was changed to due to the intensity and the pressure. Cotton fiber is used in the denim industry in different forms as organic cotton and recycled cotton. The use of recycled cotton has a positive effect on the environment and has good physical performance properties [44]. In the use of organic cotton, in order to reduce environmental impacts in the denim sector, regulations such as limiting or prohibiting the use of fertilizers and pesticides in organic cotton are made. Denim fabrics produced using organic cotton are seen as a more sustainable alternative to denim fabric produced with conventional cotton in the entire environmental impact process. The environmental damages and health hazards caused by cotton fiber have caused the denim industry to turn to alternative ecological fibers other than cotton. When the studies conducted in recent years are examined, it is seen that the amount of cotton in denim has decreased and ecological fiber blends for green denim such as hemp, bamboo, tencel, linen, soybean, viscose, and ramie are used. Physical and mechanical properties of some eco-friendly fibers in denim fabric are given in Table 1.

Hemp fiber, which is notable for its rapid growth compared to cotton, has very little water consumption and the need for herbicides or pesticides. The carbon footprint of cotton is 4.2 tons per ton, while that of hemp is 1.9 tons per ton. In addition, hemp fiber has moisture retention, breathability, UV resistance, antistatic, antibacterial, and hypoallergenic properties (Figure 4 [a]) [45]. Denim fabric containing bamboo viscose fiber has high air, and moisture permeability, elastic structure, antibacterial properties and soft-touch. Being a new kind of regenerated cellulosic fiber, bamboo viscose fiber, it is thought that its applications in the field of denim will increase due to its high tensile and tear strength properties (Figure 4 [b]) [46]. Tencel, the only man-made cellulosic fiber that performs relative to cotton, is a silky and shiny fabric. Tencel ™ denim, which contains at least 40% lyocell, is extremely durable and extremely comfortable compared to cotton denims. Tencel ™ is extremely breathable, absorbs moisture and has better performance characteristics compared to cotton [47]. Linen is a natural fiber made from the flax plant that is grown with minimal pesticides and water usage. Linen is a cellulosic fiber and its chemical treatment is similar to cotton properties (Figure 4 [c]) [48]. Chun et al. [49] observed that although linen denim showed antibacterial properties, the addition of flax did not increase its antibacterial properties. Soybean fibers have a soft and silky texture, providing a comfortable feel to denim garments and strong and durable, long-lasting, and hard-wearing material. Uzun [50] studied in her thesis, it was seen that soy protein fiber can be used in denim fabrics and sportswear fabrics with or without elastane, with 90% cotton-10% soybean, 70% cotton-30% soybean and 50% cotton-50% soybean protein blends. In the fabric performance tests, it was observed that soy fiber did not provide a performance-reducing effect. In addition, soy protein fibers has between 10-13% moisture absorption properties [46]. Viscose, also known as rayon, is a regenerated and semi-synthetic fiber made from cellulose. Ma et al. [51] created regenerated cellulose fiber from recycled waste denim. They observed that the produced regenerated cellulose fibers have mechanical properties and morphology similar to viscose fibers commonly used in the textile industry. Ramie is known for its durability, strength, silky lustre and natural resistance to bacteria and mildew, and it reduces to wrinkling. In addition, ramie is not as strong as cotton, but use as a good denim material in a blend [48].

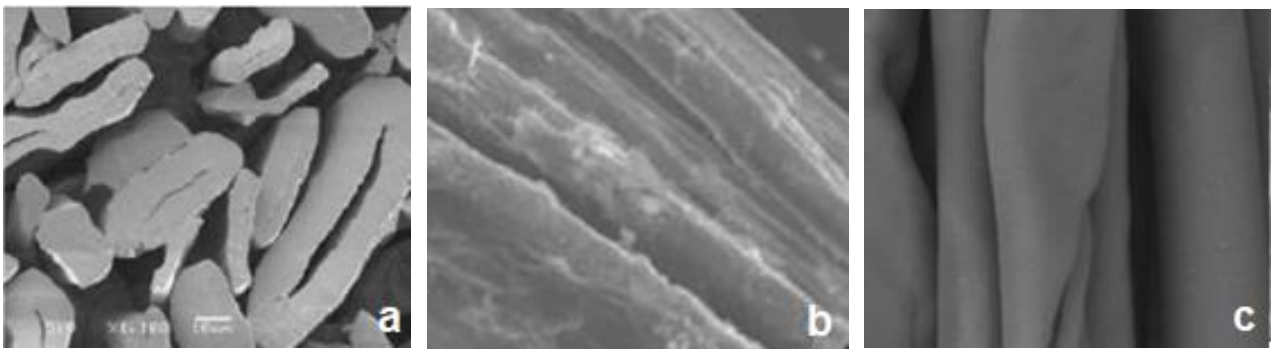

Figure 4. Microscopic View of Bamboo [a][52], Hemp[b][53], and Linen [c][54] Fibers

Table 1. Physical and mechanical properties of some eco-friendly fibers in denim fabric [48, 55, 56, 57]

Properties / Fibers	Length (mm)	Fineness (dtex)	Tenacity (cN/dtex)	Breaking extension (%)	Density (g/cm^3)
Bamboo	38-76	1,3-5,6	2,33	23,8	0,8-1,32
Hemp	300-400	9,63	3,7-4,5	35-45	1,48
Soy protein	38-76	0,9-3	3,8-4,0	18-21	1,29-1,31
Viscose	38	1,24	2,32	22,17	3,2

4.2. Recycled Denim

Denim recycle is the process of transforming used or waste denim into new products, reducing waste and conserving resources in the textile industry. The process involves collecting and sorting used denim garments or scraps, shredding them into fibers, cleaning and carding the fibers, spinning the fibers into yarn, and finally weaving the yarn into new denim fabric. This process is eco-friendly as it reduces the amount of waste generated by the textile industry, conserves resources, and reduces the carbon footprint associated with the production of new denim products.

Denim clothing consumption is widespread all over the world. Other dangerous chemicals such as cadmium, mercury, and lead, which are the remains of denim finishing, are also dumped into water sources. In addition, in the denim attrition process, coloring with toxic dyes, acid baths and sandblasting, and then chemical baths are made. Denim production, which uses a lot of water and chemicals, causes many harms to the environment, drinking water and people [58]. Non-biodegradable denim waste pollutes the environment by polluting and decomposing groundwater, producing the greenhouse gas methane [59]. With recycled denim, it is aimed to prevent these damages and to protect natural resources.

Recycling of waste in denim is divided into two as during denim production and post-consumer recycling. In denim jeans production, cutting waste is between 10% and 15% and this part is recycled by dissolving and reusing the fibers. Denim fabrics with cut waste are recycled by unwinding and reusing the fibers in additional yarn production (weft direction) [60]. There are color and fiber quality differences in post-consumer denim recycling. In addition, operations such as separation of non-textile parts such as buttons, zippers, rivets, and labels are required. Metal detectors are used to remove metal buttons and zippers. The recycled fibers from the separated pieces (can be seen in figure 5.) can also be used in open-end spinning [61]. Alp [62] produced denim fabrics from Open-End Rotor weft yarns in different blends in thesis study. He concluded that when the recycled cotton ratio increased, the weft direction breaking strength, warp and weft direction tearing strength, relative water vapor permeability, thermal conductivity, thermal absorptivity values decreased and the thickness values increased.

Figure 5. Recycled denim fibres [61]

With the government laws, regulations are being developed to reduce the solid waste management program, landfill through reuse and recycling [47]. For example, an average of 14 kilos of clothing is consumed in Sweden each year and 7.5 kilos of this is thrown away. Discarded clothing and textiles are often directly incinerated. When the waste is incinerated, there is a risk that the entire ecosystem will be exposed to combustible gases (KEMI). If not incinerated and disposed of in landfills, there is a risk of leakage and release of toxic substances from the clothing. For this reason, studies are carried out to separate textile wastes in Scandinavian countries [63].

4.3. Eco Labels for Denim Production

In the near future, policies such as sustainable denim production, increasing global warming, depletion of natural resources, and reducing the use of chemicals and energy are turning to the eco-labelling system. For this reason, it is necessary to monitor and report the carbon footprint at every stage of denim production, from raw materials to finishing and washing, transportation of finished products to transportation and consumer use. More than 40 eco-labels containing sustainable information such as "ethical", "eco-friendly", "organic" and "fair trade" are used in the textile and apparel industry [64]. The main ecological labels widely used in the world are EU Eco-Label, Bluesign, Blue Angel, Swan or Nordic Ecolabel, GOTS (Global Organic Textile Standard), Organic Exchange (Organic Content Standard), OEKO-TEX Standard 100 are listed as. n the EU-Eco-Label, some criteria have been determined by controlling the residues formed in the production of the fiber, air and water pollution, processes, chemicals used, purpose of use and life cycle of the product. There are decisive criteria for all natural or synthetic fibers used in a product [65]. Another widely used eco-label is the Bluesign label. This effect is used in applications for human and environmental protection such as reducing water use, CO_2 emissions, use of harmful substances, preventing the formation of environmental effects, ensuring consumer safety, and using environmentally friendly textiles [66]. The purpose of using another eco-label, Blue Angel has been to address environmental and health-related aspects of products and services. In addition, it is stated that Blue Angel eco-label users must comply with the basic principles and universal human rights specified in the basic labor standards in the production chain of the International Labor Organization (ILO) [67]. The Swan or Nordic ecolabel examines the entire life cycle of the textile product and all materials, including the accessories that make up the product, must comply with Swan standards. The production of the raw material in a textile product, the chemicals used in the processes of the product and the resources are evaluated separately [65]. It is a sustainable production and consumption-oriented approach that includes elements such as prevention of environmental destruction, reduction of emissions and waste, use of non-toxic materials and social responsibility. The GOTS label is the global standard for textiles using organic fibers. A high level of environmental and social responsibility is expected at every stage of the supply chain until the GOTS label is affixed to the product. It is necessary to document and evaluate all the inputs and accessories used in the creation of a textile product. This process continues from the organic structure of the fiber to the wastewater treatment structure of the enterprise, to its social responsibility [68]. For example, sandblasting of denim is prohibited as per the GOTS certificate, because of it puts worker health. Organic Exchange (Organic Content Standard), another global standard, detects the presence and amount of organic material in a final product. It examines the process of a raw material from the source to the final product and this process is approved by the expert. OEKO-TEX Standard 100 is a standard developed for the production of textile products that will not pose any risk to health and will not contain harmful chemicals. With the OEKO-TEX standard, textile raw materials, intermediate and final products are tested at all processing stages. Risks to human health in cases such as inhalation, ingestion, and skin absorption of harmful substances are controlled by regular control tests [69].

5. SUSTAINABILITY OF DENIM PRODUCTION PROCESSES

Sustainability in denim production continues throughout the entire life cycle of denim products, from raw material sourcing to manufacturing, transportation, use and disposal. Chemical management in denim production is the most important step in terms of sustainability. The careful and responsible handling of chemicals used in various stages of denim production, such as dyeing, finishing, and washing, helps to reduce environmental impacts.

There are various processes that can be used in denim dyeing, including rope dyeing, slasher dyeing, and continuous dyeing. Sustainable aspects of denim dyeing may include the use of eco-friendly and biodegradable dyes, reducing the amount of water used in the dyeing process, and implementing closed-loop systems that allow for the recycling and reuse of dyeing chemicals and water. There are several processes that can be used in denim washing, including stone washing, acid washing, bleach washing, enzyme washing, and laser fading. Each process achieves a different look and effect on the denim fabric. However, it is important to consider the environmental impact of these processes and prioritize the use of sustainable techniques such as laser fading and ozone washing. In this section, sustainable chemicals and methods used in denim finishing process will be explained.

5.3. Dyeing in Denim Products

Denim generally are customed dyed with indigo to produce brilliant blue shades with the desired wash effect. This rate is about 80% of denim worldwide being dyed in classic blue, black-blue or blue-black tones using indigo and sulphur black dye. Apart from these dyes, the remaining 20% denim products are dyed in different tones using sulphur for reduce cost, indanthrene, and another dye class [70-72]. Indigo can be dyed into cotton fibers very well. The best feature of indigo dyed jeans is the possibility of obtaining wash effects without losing the freshness of the color in repeated washings [72]. Indigo is a naturally water-insoluble dye and therefore an alkali and reducing agent must be converted to a soluble form before it can be applied to denim warps [73]. For indigo dyeing, 84 500 tonnes of sodium hydrosulphite and 53 500 tonnes of caustic soda are required each year [74]. In addition, İndigo dye has heavy metals and hazardous pollutants. Indigo is very difficult to decompose biologically, and high concentrations of indigo dye waste in the resulting effluent could damage to environment [75]. For these reasons, it is used synthetic indigo contains toxic chemicals such as aniline and N-methylaniline residues in denim dyeing. Apart from synthetic indigo, denim products are dyed with sulphur, reactive pigment, and direct dyestuffs. Most of these dyes contain heavy metals such as chrome, copper, and zinc [71]. Since indigo is insoluble in water, it mixes with wastewater and causes significant environmental damage. For this, conventional treatments such as activated sludge biological plants or/or coagulation-flocculation processes are applied. Membrane techniques, which are a sustainable approach to recover and reuse both chemicals and water by purifying wastewater, are being developed [76]. Another method for reduce environmental waste, the use of natural dyes could be used in denim production. It is possible to obtain different tones on denim by using environmentally friendly mordants such as onion extract, natural and synthetic mordant. Natural indigo may have important additional properties, including potent antimicrobial activity against various pathogens, anticancer activity, antioxidative activity, and UV-repellent properties [74]. Sustainable indigo dye can be made using natural indigofera plants, which are renewable resources that can be grown without harmful chemicals. Tia et al. [77] observed that natural indigo could be stabilized on a nanocellulose matrix carrier without chemicals, making the dye more ecologically safe to use on cellulosic materials. Natural indigo is biodegradable and using natural indigo reduces the amount of synthetic dyes and chemicals used in the dyeing process. However, it will be generally more expensive and time-consuming to produce than synthetic indigo, and the color will vary depending on factors such as the plant source, climate, and processing methods.

5.4. Desizing in Denim Products

Desizing, which applied to warp yarn, is the process to strengthen the yarn for weaving. The most used method of removing starch from denim products is to use amylase enzyme. Amylase enzyme is break down the long starch molecular chains (water insoluble) into smaller molecules (water soluble) which can be more easily washed away. Generally, enzymes are environmentally friendly and do not creating health hazards but sometimes they could be skin irritation. For sustainable desizing in enzyme, operators should use self-protective clothing such protective wear, hand gloves, safety goggles and face masks [39, 71].

5.5. Mercerization Process in Denim

Mercerization is the treatment of pure cotton fabric or yarn with a strong causticizing agent to significantly increase the strength of the dye and the strength and smoothness of the yarn. Then, the caustic soda is removed by washing. In denim, the fabric is held under tension using a strong sodium hydroxide solution (approximately 18-24%) and washed off the caustic after 1-3 minutes [78]. Caustic soda removed by washing causes environmental damage. Varol et al. [79] achieved caustic recovery from mercerized wastewater originating from a denim textile manufacturing facility by using membrane technology. Thus, they aimed to prevent environmental problems for caused by caustic material with high pH (12-13) values in wastewater. Yükseler et al. [80] observed that methods such as Best Available Techniques for the treatment, reuse, and reduction of wastewater amount in dyeing and nanofiltration for the recovery of caustic from wastewater can be effective. They achieved satisfactory results in meeting wastewater reuse criteria by providing a 30% reduction in total specific water consumption in denim production.

5.6. Fading Technologies in Denim

Sustainable fading techniques in denim production typically involve the use of innovative technologies and processes that reduce the environmental impact of traditional denim washing and finishing methods. These techniques include enzyme fading process including eco-friendly chemicals, ozone fading process and laser fading process. In addition, it is aimed that the reuse of water in the washing process to reduce water consumption and pollution. In this section, these sustainable fading techniques will be explained.

5.6.1. The Enzyme Fading Process

To fading denim fabrics, the products are washed with pumice stone and partially bleached with sodium hypochlorite, neutralized, and washed again. Since all these processes cause great environmental pollution, bleaching is done with enzyme applications. Since the cellulase enzyme has a cleansing effect on the fiber surface, it can partially replace the pumice stones to obtain the stone washing look. Laccase enzyme that works faster than traditional bleaching techniques [51], has the feature of bleaching indigo dyed denim clothes to lighter shades [81]. Kan et al. [82] investigated the effect of enzyme treatment using neutral cellulase on the colour fading properties of cotton denim fabrics. They observed that denim fabrics treated under optimum condition retain the best color yield with the desired aging effect. In addition, cellulase has property as catalyses the hydrolysis of cellulose molecules' 1, 4-beta glycoside bond and so it produces less pollution and is easier to treat in effluent plants [47]. Uses enzyme in denim fabrics for fading are both sustainable and efficiency approach.

5.6.2. The Ozone Fading Process

Ozone (O3), can be used to create the color fading effects in denim [83], can be utilized to oxidize many organic and inorganic impurities [84]. Ozone can be applied directly as the gas phase without a water bath, thereby reducing water consumption significantly. Being an environmentally friendly substance, ozone is seen as a very good option for substances such as hydrogen peroxide and chlorine bleach [85]. Ozone fading is a sustainable process which could use no chemicals and no waste. Because ozone has very high oxidizing power, it can attack the glycosidic bond of cotton fiber and has an effect that can break down the olefinic groups of indigo dye. Thus, ozone is a sustainable alternative that can be used in bleaching denim fabrics [86]. Rajkishore et al. [83] listed 4 sustainability benefits of ozone bleaching over traditional bleaching methods. These benefits are environmental, economic, social, and production benefits. Ozone bleaching is a method that reduces environmental pollution and does not cause wastewater generation and recycling problems. Economically, the consumption of chemicals, water and energy is low. As a social benefit, it reduces the workload, and fatigue of the employees. In terms of production, the ozone bleaching process is faster, thus saving energy and operating costs. Besides its sustainability feature, ozone is an effective oxidant and disinfectant that can break down the cellular structure of viruses, parasites, and bacteria. It has some advantages over chlorine, which is widely used in the textile industry, such as not being permanent and not leaving secondary derivatives [87]. Ozone washing taking attention with minimal production costs and high production capacity system enhances whiteness and eradicates the back staining as well as other potential organic spots (Figure 6.) [88]. Another important issue in the use of ozone bleaching is the effects on the physical and mechanical properties of denim fabrics. Ben Faraj et al. [86] observed that ozone treatment had significant effects on the mechanical and color properties of denim, such as the loss of force at break and the decrease in the bagging resistance. For this reason, they suggested that denim fabrics should be treated with medium-intensity ozone for a short time.

Figure 6. Before and After Ozone washing in denim [88]

5.6.3. The Laser Fading Process

Sustainable laser fading technology is an innovative and eco-friendly technique of fading denim fabrics, which has been gaining popularity in the denim industry as a more sustainable alternative to traditional methods such as sandblasting and acid wash, bleach wash, stone wash, and enzyme wash [89]. Sustainable laser technology has several advantages over traditional methods, including reduced water and chemical consumption, energy consumption, and process flexibility, as well as reduced environmental pollution. The laser fading process can be easily applied to ab industrial processes for more detailed and complex designs to be created [90]. The laser creats extensive heat in denim fabric. Laser energy is absorbed as taking heat and the material rapidly heats occur melting as a phase change from solid to liquid takes place on denim. Laser fading works with a burning mechanism [91]. The fading efficiency is related to the laser wavelength, power density, exposure time, and beam width (Figure 7.) [92]. Also, laser fading is a popular computer-controlled process on denim products. Laser fading works with better accuracy and higher productivity than other bleaching methods. Many types of lasers are used in denim laser fading. These are medium of laser that may be a solid (e.g., Nd: YAG), gas (e.g., CO2, Ne), or liquid (dye). In literature, color fading, the following laser medium, including Nd: YAG, CO2, and CTH: YAG was seen. Especially, Nd: YAG processes have a shorter wavelength and are best suited to the pulsed application mode,which includes smaller coverage, deeper penetration, and precision machining for specific purposes [93]. Some researchers have concluded that CO2 laser [93-95] more efficient utilizing low heat generation, clean production and low cost. Color fading with CO2 laser is widely applied in the textile industry [94]. Ortiz et al. [95] observed that CO2 laser bleaching has higher efficiency, lower energy waste, less heat generation, simpler and cheaper cooling systems, and less water consumption than other laser types. In another study, Kan [96] concluded that the CO2 laser process is a cleaner production method for color fading of denim fabric than other methods, and that high laser power creates paler tones in denim fabrics. Similarly, Venkatraman and Liauw [97] investigated the performance properties of indigo dyed denim fabrics of different densities after CO2 laser bleaching. As a result of the study, they observed that the degree of grayscale affects the color change and increases color fading in all kinds of fabrics, as the increased structural damage in the cellulose polymer will increase as the grayscale level increases. However, in the study by Chow et al. [98], it was concluded that in the laser bleaching process, the laser level causes thermal degradation on the cotton fabric, and the chemical composition of the treated cotton fabric surface changes. From this point of view, keeping the CO2 laser level at an optimum level is the right approach. In addition, the appropriate level of laser level is also an important issue for the health of textile workers. Lasers with deadly voltages contain hazards such as electric shock, vision loss, and skin injury. To reduce these hazards, training of working personnel, use of protective equipment, administrative and engineering controls should be carried out [99].

Sakib et al in their study, were determined of color fastness to rubbing in laser fading for denim fabrics. They were seen that non-wash condition and the wash condition of the denim fabric wet rubbing is so different for fastness in laser denim [100] The LEVI'S Standards (LS&CO. Global Fabric Performance Standards) suggest that denim fabric has very low wet rubbing fastness. In addition, according to OEKO-TEX standards, the pH reference range that should be in denim fabrics is between 6 and 7.5. In their study, Tölek and Kadem (2016) stated that a standard cotton denim fabric has a color fastness to light 5, pH 5.5, color fastness to wash 3, color fastness to rubbing -shade change in dry 5, in wet 3-4 [101].Wash fastness is related to the adhesion of nanoparticles to the fibers, and it is possible to increase the washing fastness by immersing the nanoparticles fabrics in a solution containing a certain binder. Thus, covalent bond formation can occur between nanoparticles and the fabric surface. Nano-Ag process is applied to increase washing and light fastness [102]. In addition, with synthetic indigo dyes used in denim fabrics, the fastness and washing properties of the textile material can be improved by factors such as pH and number of dips [103].

Figure 7. Laser Fading Process in Denim Fabrics [91]

5.7. Washing Technologies in Denim

Sustainable washing process in denim refers to a method of washing denim garments without causing harm to the environment or using excessive amounts of water and energy. This process is aimed to reduce the environmental impact of denim production by adopting eco-friendly practices. Washing with natural materials and water reduction technologies in the washing process, which are frequently used in sustainable washing, are described in this section.

5.7.1. Washing by Natural Resources

Due to the use of chemicals and stones in denim washing processes, a waste problem arises that questions the sustainability of the process. For this reason, efforts are being made to develop a denim washing process with ecological washing techniques that can result in zero waste discharge. Dry processes or nearly waterless processes are slowly becoming a sustainable trend to replace traditional wet processes in denim garment washing [35]. Shibly et al [104] observed in their studies, the washing effects natural reagents such as lemon, pomelo, guava, ginger, and spondias mombin on indigo dyed denim fabric. The use of natural reagents in denim washing provides less polluting natural washing. Hoque et al [105] focused on in their studies washing 100% cotton indigo dyed denim garments with natural substances like soapnut, lemon juice, tamarind, and sunlight. Natural washed samples were seen less amount of shrinkage as well and greater strength and less color difference values than the samples washed by synthetic chemicals (Figure 8.). Using natural agents in washing denim are seen optimum eco-friendly method for sustainability.

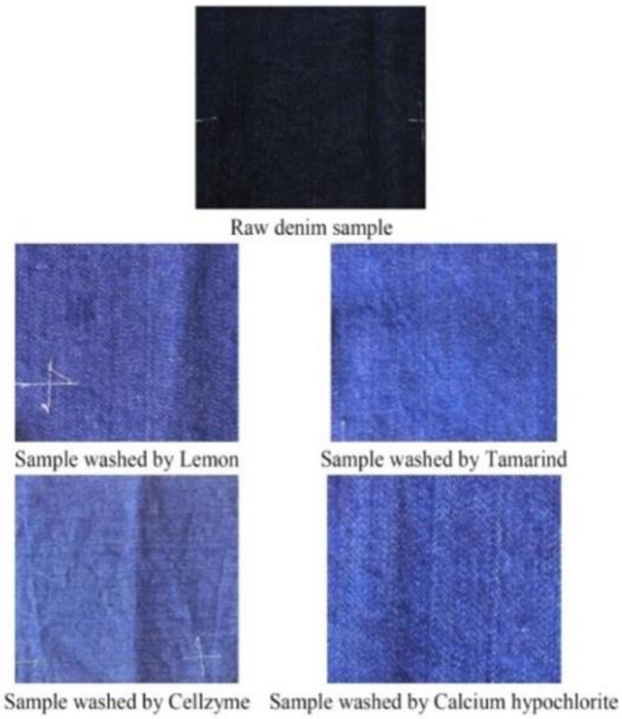

Figure 8. Color difference on fabric samples washed by natural and synthetic reagents [105]

5.7.2. Water Reduction Technologies

Reduced water washing techniques are a set of denim washing techniques that are designed to conserve water and reduce the environmental impact of denim production. These techniques use less water than traditional washing methods and rely on alternative methods to achieve the desired effect. These sustainable washing techniques are those that can obtain a washed look and excellent handle using a minimum quantity of water [36]. These washing techniques are classified as using laser, ozone, nano bubble, new enzyme formulations and crosslinking agents. How each technology can affect water consumption, and its advantages in reducing water footprint comes from the combination of these technologies and their use in finishing [106]. Laser technology is used to create the desired fading and distressing effects on denim faster and without the need for water. Kan (2014) [107] concluded that traditional denim washing requires more rinse steps and laser treatment can save water in the manufacturing process. While the denim design, which was created with the classical method, was created by washing the stone with an enzyme for 45 minutes at 55 °C, the same design was produced by laser process within 3 minutes at room temperature. This shows that laser fading saves energy, water, time, and chemicals compared to the traditional process. Another reduced water washing technique is ozone technology, which uses ozone gas to bleach and fade denim, which reduces the need for water and chemicals. Ozone gas is produced by an ozone generator and is injected into the washing machine during the wash cycle. When the cycle is over, ozone is converted back to oxygen and this oxygen is released back into the atmosphere [106]. In addition to being a clean process, ozone is a type of washing that can provide good performance properties. In their studies, Kamppuri and Mahmood [108] observed that wet ozone washing, in which ozone dissolves in water, can bleach jeans and reduce back staining without a significant loss in the strength of the fabrics. Another eco-friendly washing is the nano bubble technology technique used in denim washing for reduced water consumption which involves the use of water infused with ultra-fine bubbles. These tiny (1mm) bubbles have a diameter of less than 100 nanometers and are highly pressurized, allowing them to penetrate deep into the denim fibers and remove impurities without the need for large amounts of water. A minimum amount of water is required in the nanobubble technique and there is zero discharge from the process. Air from the atmosphere is fed into an electroflow reactor and subjected to an electromechanical shock that creates nanobubbles and a stream of wet air [109]. To reduce the use of water in denim washing, there are also the use of some enzymes and cross-linking agents in addition to the machine technologies mentioned above. The use of cellulase enzymes instead of alpha amylase enzymes in desizing and abrasion processes in denim processing reduces the need for both washing and rinsing. At the same time, the use of cross-linking agents such as glyoxal resins in denim finishing is a new approach that reduces the need for water in denim washing. The crosslinking agents possessed by glyoxal resins have a strong effect on fabric strength as sustain a significant change in fiber structure. Thus, the loss of strength can be controlled. In addition, this property is used to embrittle, break and eventually remove the fibers from the surface through dry mechanical action. This abrasion is effectively produced by dry pumice stones so that denim production does not need water to achieve the highs and lows and increased white and blue contrast in the stitching and fabric panel [106]. These reduced water washing techniques in denim washing described above not only reduce water usage but also reduce the amount of energy and chemicals required, resulting in a more sustainable denim production process in all denim production processes.

6. CONCLUSIONS

Overall, sustainable denim production involves a holistic approach that considers the entire life cycle of denim production, from raw materials to finished products. In order to implement sustainable denim production correctly, first of all, it is necessary to understand sustainability and its basic approaches correctly. Sustainability is a comprehensive practice consisting of environmental, economic, and social components. In this study, the denim production process, eco-friendly denim, and recycled denim products used in denim production and sustainability practices applied in dyeing, desizing, mercerization, fading and washing processes were explained. In the scope of the study, it was seen that sustainable denim production reduce the environmental impact of these processes by minimizing water usage, using renewable energy sources, and using safer, eco-friendly materials.

It is possible to summarize the sustainable denim approaches obtained within the scope of the study as follows:

- Both organic and recycled cotton can be used in the production of denim fabric. When used, these sustainable materials can help reduce the environmental impact of denim production by reducing the use of synthetic materials, conserving water, and reducing waste.

- Ecological fiber blends such as hemp, bamboo, tencel, flax, soybean, viscose, ramie have used as the amount of cotton in denim decreases. Using these alternative green fibers in denim production, it could reduce the environmental impact of denim production by reducing the use of synthetic materials, conserving water, and reducing waste.

- The process of creating recycled denim often uses less water and energy than producing new denim from scratch, making it a more sustainable and eco-friendlier alternative. Recycling of waste in denim is divided into two as during denim production and post-consumer recycling. Approximately 10% and 15% denim cutting waste are recycling by dissolving and reusing the fibers. In post-consumer denim recycling, generally are produce Open-End Rotor weft yarns from second hand denim waste.

- An eco-labelling system in textiles is crucial for promoting sustainable and environmentally friendly practices in the textile industry. Protection to global warming, effective use of natural resources, and reducing the use of chemicals and energy are falls within the scope.

- Indigo is often used in denim dyeing and since indigo is insoluble in water, it ends up in wastewater, causing significant environmental damage. For this reason, the use of natural indigo reduces the use of synthetic dyes, wastewater and chemicals used in the dyeing process.

- Sustainable desizing process uses amylase enzyme, mercerization process uses best available techniques for dyeing treatment, reuse, and reduction of wastewater and nanofiltration for caustic recovery from wastewater.

- Sustainable fading process in denim refers to a method of achieving a worn or faded appearance on denim fabric without using harmful chemicals or excessive water consumption. This process generally include enzyme fading process, ozone fading process and laser fading process. In enzyme fading, cellulase enzyme has a cleansing effect on the fiber surface and it produces less pollution. Ozone fading is a sustainable process which could use no chemical and no waste. Ozone fading is a sustainable method that reduces environmental pollution, the consumption of chemicals, water, workload and fatigue of the employees and is faster. Sustainable laser technology has several advantages such as reduced water and chemical consumption, energy consumption, and process flexibility, could produce more detailed and complex designs. Kan (2014) [96] seem that CO2 laser process is a cleaner production method in color fading of denim fabric than other fading methods, and that high laser power could create paler tones in denim fabrics.

- Sustainable washing process in denim refers to a method of washing denim fabric and garments using eco-friendly and low-impact methods that reduce water consumption, chemical usage, and environmental impact. Washing by natural resources and reduce water technologies are often used in washing process. For washing with natural materials, it could see that [104] washing effects natural reagents such as lemon, pomelo, guava, ginger, and spondias mombin on indigo dyed denim fabric. Reduce water washing techniques are included laser, ozone, nano bubble, new enzyme formulations and crosslinking agents. These techniques are both reduce water usage but also reduce the amount of energy and chemicals required, resulting in a more sustainable denim production process.

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