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An analysis of environmental and occupational health impacts of denim manufacturing and exploration of sustainable production alternatives

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Abstract

Denim is an important subset of the world textile industry. This study aims to explore the possible health impacts as well as the environmental risks caused by different processes of denim production. The present study deals with wide-ranging consequences related to the chemical processes involved in denim manufacturing, including the overconsumption of water, destruction of natural habitats, pollution, and adverse health effects on workers. It also deals with the pollution created during various steps of denim production and the subsequent carbon emissions released into the environment. This study investigated the health effects of chemicals used at different stages of denim production on workers and residents in the vicinity. This study analysed published works and literature to highlight the lack of attention given to sustainable practices in the denim industry. It also deals with the negative consequences of production of denim on the environment.

Keywords: Carbon Footprint; Biological Oxygen Demand; Sandblasting; Stone washing; Laser Technology; Ozone Fading; Sustainable Practices

1. Introduction

Denim, popularly known for its rough and tough texture, is a sturdy cotton fabric woven with a twill weave. Denim, one of the most versatile fabrics, has gained popularity owing to its suitability for all ages, seasons, and occasions. It is also expected that the market value of denim will increase to 23.9 billion US dollars by 2027 (Periyasamy & Periyasami, 2023). It is evident from the data that denim is one of the fabrics in high demand, irrespective of age and season. Earlier, this fabric was used to construct durability fabrics, such as trousers for labourers, but it later became trendy as leisure wear. Data show that China, followed by India and Bangladesh, is the leading country supplying denim worldwide. Approximately 66 % of raw denim is exported by the USA from these countries (Sünter Eroglu, 2023).

Conventional denim fabric is woven using indigo or sulphur dyed cotton yarns as the warp and white cotton yarns as the weft. Cotton warp yarns are prominent on the front surface of the fabric. In the contemporary era, it is manufactured by blending cotton yarn with polyester or elastane which adds the characteristics of elasticity and comfort to the fabric. The typical denim manufacturing process begins with the preparation of cotton yarns, followed by rope or slasher dyeing using synthetic indigo. Once dyed, the yarns were woven into a denim fabric. The fabric also undergoes additional finishing processes, such as desizing, stone washing, sandblasting, or bleaching, which ultimately gives denim its style and feel. Denim production involves successive procedures, as illustrated in the following schema chart: -

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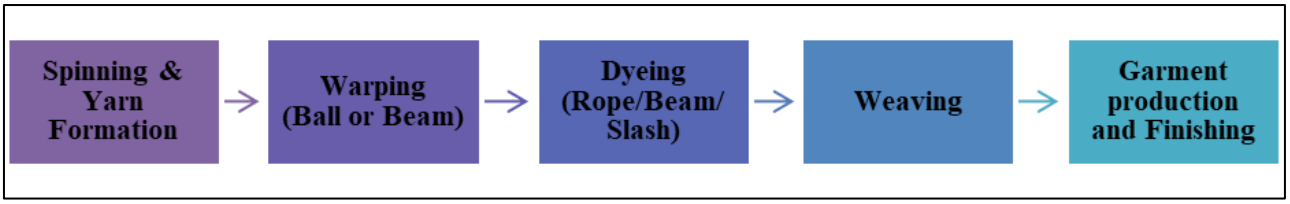

Figure 1 Schema of the Denim Garment Manufacturing Process

- Step I - Conversion of cotton fibers into yarns: Cotton fibers are converted into yarns using either a rotor spinning system or a ring spinning system. This process involves cleaning the fiber, carding, drawing, roving, and spinning.
- Step II - Warping: In this process, multiple yarns from individual yarn packages are transferred to a single-yarn package assembly. This can be performed in two ways: Ball and Beam warping (Wagner, n.d.)
- Step III - Sizing: This is the process of confining warp yarns with a protective coating. Common materials used for sizing yarns are modified starch, acrylates, polyvinyl alcohol, carboxymethyl cellulose, and wax. Sizing primarily aims to enhance the durability of yarns against abrasion during weaving, minimise yarn hairiness to prevent unravelling at the loom, and prevent the indigo dye from rubbing off during the weaving process.
- Step IV - Weaving: It is woven on shuttle loom/projectile loom/rapier loom or air-jet loom using a twill weave where the weft passes under two or more warp yarns. In addition to twill weaves, plain and satin weaves are sometimes used to weave denims.
- Step V - Finishing: To provide a shiny, non-rolling, soft, and smoother texture to denim fabrics, singeing and brushing processes are performed, followed by washing and drying.
- Step VI - Garment Manufacturing: The finished fabric is stitched into garments such as jeans, jackets, and skirts.
- Step VII - Special Finishing: To impart textures to the denim garments, different chemical and mechanical washing processes were carried out. Chemical washing includes enzyme washing, denim bleaching, and acid washing. Mechanical washing involves stone washing and sandblasting (Kiron, 2021). Denim washing can also be classified as wet and dry washing. Wet washing comprises enzyme washing, stone washing, softening, bleaching, etc., whereas dry treatments include manual damage, scraping, tagging, sandblasting, laser, and resin.

2. Carbon Footprint associated with denim manufacturing:

Carbon footprint is associated with the greenhouse gases emitted during the manufacturing of a product. Carbon dioxide, methane, nitrous oxide, and fluorinated gases are the primary greenhouse gases. Each of these gases possesses a distinct global warming potential, which is globally standardized using carbon dioxide equivalents (CO2e). According to a report by the US Energy Information Association, the textile industry is the 5th position in contributor to CO_2 emissions, followed by metallic compounds, non-metallic mineral items, chemicals, and petroleum. Cotton is the primary raw material used in denim manufacturing. It is obtained from natural sources and is believed to be sustainable, but research has revealed that to attain the desired quality of cotton from cotton plants, substantial quantities of pesticides and fertilizers are required. In their study titled "Carbon Footprint on Denim Manufacturing", Periyasamy and Duraisamy stated that to produce 1 kg of cotton, approximately 7-9 tons of water is required, and it also generates greenhouse gases such as CO_2,, CH_4 and N_2O in substantial amounts (Periyasamy & Duraisamy, 2021). Greenhouse gases are emitted in the different stages of denim production.

Cotton, the primary raw material for denim manufacturing, requires a remarkable quantity of water, fertilizers, and pesticides for production which in turn significantly contributes to greenhouse gas emissions. It is estimated that approximately 7 tons of carbon dioxide is released by the mere usage of 1 ton of nitrogen-based fertilizers. According to the report of the International Cotton Advisory Committee's Panel on Social, Environmental, and Economic Performance, the greenhouse gas emission per hectare of cotton production ranges from 0.15 to 4 tons of carbon dioxide equivalents.

The entire manufacturing process of denim garments, from yarn creation to the final apparel, comprises resource-intensive steps that emit carbon dioxide into the atmosphere. A study carried out by Levi Strauss and Company reported that approximately 3,781 liters of water is consumed in the manufacturing process of a single pair of jeans, and it can release up to 33.4 kg of CO_2 into the atmosphere (Strauss, 2015).

The scrapping of jeans either through incineration or landfilling also contributes significantly to the emission of greenhouse gases. It takes a long time for jeans to decompose. During this process of landfilling, harmful greenhouse gas, such as methane, are released and toxic substances leach into the soil and groundwater.

3. Environmental and Health Hazards of Denim Production

Denim, known for its versatility, durability, and iconic fashion status, is one of the most widely worn textiles globally. The conventional manufacturing process per kilogram of denim releases approximately 40–65 L of pollutants that are released into water sources, causing water pollution. It has a substantial environmental impact, encompassing the harmful use of chemicals, significant carbon emissions, and excessive water consumption. Pollutants are released into the environment at four stages of denim production: cotton cultivation, dyeing, finishing, and distribution, particularly during sizing, dyeing, desizing, bleaching, antichloro wash, stone wash, and softening processes. These pollutants include unfixed dyes, starch, oils, fatty acids, sodium/ disodium thiosulphate etc. The prime raw material in the conventional denim manufacturing process is cotton. Murshida Khatoon and their team reported cotton as one of the most hazardous crops as it consumes approximately 25 % of the total insecticides and 12 % of the total pesticides used globally (Khatun et al., 2024). When released into the environment, these chemicals have detrimental effects on human health and the surrounding environment (Chakraborty et al., 2022).

Another significant issue related to denim manufacturing is the increase in the level of Biological Oxygen Demand (BOD) in Indian rivers. It refers to the oxygen required by microorganisms to break down organic matter in water resources. It is a crucial environmental indicator associated with the wet processing stages of denim manufacturing. The wet processing stages, such as desizing, scouring, dyeing, stone washing, and enzymatic treatments, pose consequential health risks, such as waterborne diseases, damage to aquatic ecosystems, and long-term health consequences from hazardous substances. The effluents generated at different stages of denim manufacturing, particularly from dyeing and washing processes, contain chemicals, organic matter, and other harmful agents that deplete oxygen in water bodies, leading to oxygen-deprived (hypoxic) conditions. This makes the water unsuitable for use and harms marine life. The main sources of pollution in the dyeing process are dyes, auxiliary substances, and other chemicals. (Periyasamy & Periyasami, 2023). Heavy metals such as cadmium, chromium, and lead are found in dye molecules and can have harmful effects on body organs. Additionally, low levels of dissolved oxygen can harm ecosystems by causing suffocation in aquatic animals. To minimize the BOD levels in wastewater before discharging it into water bodies, efficient effluent treatment plants are required.

The production of denim poses health risks as a result of the application of toxic dye auxiliaries and chemicals, such as heavy metals, during both the dyeing and finishing stages. These substances can jeopardies workers and pollute water supplies, threatening both human health and the environment. Additionally, the use of sandblasting and other chemical washing techniques further exacerbates the health risks for workers and ecosystems.

To enhance colour vibrancy and stability, heavy metals are used in the dyeing process of denim which incurs potential health risks, such as damage to multiple organs, potential carcinogenetic diseases, and birth defects. The presence of heavy metals in dyes poses a potential threat to absorption via the skin, leading to dermatitis, irritation, and allergies. Chromium, which is used as a mordant to adhere the dye to the fabric surface, can cause liver damage, pulmonary congestion, and cancer (Chakraborty et al., 2022).

Denim dyeing is done traditionally with synthetic indigo dyes, in which sodium hydrosulphite and sodium hydroxide is used as reducing agents, resulting in discharge of hazardous wastewater in to water resources. Untreated wastewater released from denim manufacturing plants contains high concentrations of chemicals and heavy metals, the exposure to which leads to long-term health consequences.

Sandblasting imparts a distressed and faded look to the denim. In this process, denim fabric is exposed to very high-speed propulsion of very fine abrasive materials, especially silica sand. This erodes the top layer of the fabric, imparting a weathered look to the garment. In many countries, sandblasting is banned owing to its potential health risks for the workers associated; however, because of its efficiency in imparting the desired appearance to denim at an affordable price, it continues to be used clandestinely in certain parts of the world. Inhalation of silica dust may cause severe respiratory illnesses such as silicosis, a life-threatening lung condition. (McIlvride et al., 2014)

Stone washing is another mechanical process applied to sewn denims to provide a worn-out or vintage look to the denim. Stones were used to roughen the surface of the fabric. Denim garments were tumbled in large industrial washing machine in addition to pumice stone. During the process, the denim surface is repeatedly abraded with stone while the tumbler rotates, giving a distressed look to it. The temperature, washing time, shape, size, and hardness of the stone

indicate the intensity of its weathered appearance. The traditional stone washing process consumes a significant amount of water. Moreover, the broken pumice stone generated during the process turns down into sludge. This sludge often ends up in landfills or waterbodies, contributing to environmental pollution. In this process, pumice stones are often combined with bleach or potassium permanganate, which when released untreated into waterways, disrupts ecosystems and severely damages aquatic life.

Microfibers are released during the washing and wearing process of denim, which is likely to be ingested by aquatic animals, and thus enter the food chain, leading to health issues. The constant abrasion involved in stone washing causes microfibers to shed from denim fabrics that contain synthetic blends, often leading to their entry into aquatic environments, where they pose a threat to marine organisms. These microfibers do not break down naturally and can be built up in the food chain.

4. Sustainable Alternatives

Considering these issues related to conventional denim manufacturing processes, several sustainable alternatives have emerged that significantly contribute to reducing carbon emissions and the environmental and health impacts of the denim production process.

Use of organic and recycled cotton as raw materials: The cultivation of organic cotton does not require pesticides and insecticides. Moreover, water consumption is lower owing to improved soil health. It also enhances biodiversity and contributes to the health of farmers and local communities. As far as recycled cotton is concerned, it is sourced from pre-consumer or post-consumer textile waste, which substantially reduces the demand for virgin cotton for denim manufacturing. According to the Textile Exchange-Market and Materials report, by using recycled cotton, carbon footprints can be lowered by up to 50 % compared to conventional raw materials (*Materials-Market-Report-2024.Pdf*, n.d.).

Dyeing is one of the most polluting stages of denim production, typically relying on synthetic indigo and toxic reducing agents such as sodium hydrosulfite. Sustainably, it can be eliminated by the use of natural indigo dye (made from plants), pre-reduced liquid indigo (minimising chemical waste), and new technologies such as electrochemical dyeing and foam dyeing, which significantly reduce water and chemical usage (Zhu et al., 2022). Environmental pollution and total energy requirements can also be decreased by cold pad batch dyeing and enzyme-aided treatments.

Carbon Sequestration is another sustainable solution for reducing the environmental carbon footprint by removing CO_2 from the atmosphere and depositing it in natural or artificial reservoirs. The process of producing denim is extremely carbon intensive, especially due to the farming of conventional cotton, dyeing and finishing processes, and burning of fossil fuels during manufacturing and logistics. Emissions can be substantially reduced by integrating carbon sequestration strategies. One approach is a regenerative form of cotton farming that incorporates cover crops, reduced tilling, and organic fertilisation to raise soil organic carbon. As published by the Textile Exchange (2022), regenerative practices have the potential to sequester one to three metric tons of carbon dioxide for every hectare per year, which makes this a viable option to offset emissions predominantly related to cotton farming—the main raw material used in denim production.

Laser technology has emerged as a greenfield and leading-edge technology to address the issues of the denim finishing process of sandblasting and stone washing. This process uses computer-controlled laser beams to selectively evaporate indigo dye from the surface of the fabric to create specific washed down or worn-out patterns without the use of water or chemicals. Importantly, laser finishing significantly decreases water consumption to 0–5 litres per garment, and firms no longer use abrasive methods, resulting in a significant improvement in the health and safety of workers. The study "Carbon Dioxide Laser as an Environment Friendly Tool for Denim Fabric Patterning: An Optimization - Colour and Durability Assessment" presents the technology of CO_2 laser as an alternative finishing process to the conventional denim fabrication processes. Many traditional methods require the use of hazardous chemicals and high levels of water, resulting in health and environmental risks. This study aimed at determining the optical energy and exposure time requirements of CO_2 lasers to develop desired patterns and fading effects in denim fabrics without impairing fabric evenness. Scientists applied a CO_2 laser to indigo-dyed 100 % cotton denim fabrics with varying weights by changing the values of laser power, speed, and grayscale levels. After treatment, changes in colouration, colourfastness, fabric tensile strength, and thickness were evaluated. The results showed that laser treatments offer distinct patterns and fading effects to denims. An increased grayscale value produces stronger colour changes. Some reduction in tensile strength was noted, especially in the lighter fabrics at higher grayscale settings; however, the structural integrity and durability of the denim were preserved. Furthermore, the laser-treated fabrics maintained good colourfastness which indicates that the fabric is suitable for everyday use (Manchester Fashion Institute, Faculty of Arts and Humanities,

Manchester Metropolitan University, Cavendish Street, Manchester, UK & Pd, 2022). The laser treatment process is a viable embodiment of personalised denim designs and helps minimise harsh chemical processes. This sustainable process has the potential to transform the textile industry by saving water and ultimately lowering the impact on the environment linked to conventional denim finishing processes.

Ozone fading is a new and eco-friendly process for developing a used or retro/vintage appearance on garments in denim processing without the use of harsh chemicals. Ozone (O_3), a powerful oxidative gas, is applied in this method to degrade indigo dye in the case of denim fabric. When indigo-dyed denim is exposed to ozone gas, it oxidises the dye molecules, making them colourless and resulting in a faded appearance. The paper entitled "Eco-Friendly Ozone Process for Denim Garment as an Alternative to Conventional Bleaching" investigates ozone treatment as an eco-friendly substitute for conventional bleaching techniques for the production of denim. Traditional bleaching methods that focus on the use of strong chemicals, such as sodium hypochlorite and potassium permanganate, are hazardous to the environment and human health, imposing substantial water use and toxic effluents. Ozone, a strong oxidant, is simpler, cleaner, and more environmental friendly (Rıza Atav et al., 2024). This research discusses the efficiency of ozone in obtaining the same or enhanced aesthetics on denim articles as the traditional methods. The focus was placed on different parameters, such as colour fading, fabric strength, and environmental impact. The results demonstrate that ozone-treated denim gives the desired appearance characteristics

Industrial washing is a crucial final process that makes denim more visually appealing and comfortable, although it contributes significantly to environmental pollution due to the excessive consumption of water, chemicals, and energy. In response to these sustainability challenges, several new technologies have been developed that aim to minimise environmental impact. One such innovation, e-flow technology, was developed and patented by Jeanologia, a Spanish company. This technique makes use of nanobubbles produced by an electro-flow reactor which divides the atmospheric air into small bubbles as a result of an electromechanical shock. These oxygen-enriched nanobubbles were then injected into a tumbler containing denim garments. These nanobubbles enhance the softness and comfort of the fabric while also providing better control over shrinkage without consuming large volumes of water or chemicals. This process can reduce water use by up to 98 %, reduce energy consumption by up to 47 %, and eliminate chemical waste. Therefore, it is a sustainable option compared to traditional wet processing methods in the denim industry (Khalil, 2016).

Post-consumer waste, particularly from worn-out jeans, presents a significant challenge. However, innovative alternatives have emerged to address these concerns. Some companies are taking the initiative to shred old jeans, transforming them into regenerated fibers that can be spun into fresh yarns. Recently, notable brands have launched take-back programs aimed at breathing a new life into old denims. The closed-loop recycling approach reintroduces post-consumer denim back into the production cycle while preserving much of its fibre value. The benefits are substantial: it conserves water, minimises carbon emissions, and significantly reduces landfill waste. By mixing post-consumer denim with other eco-friendly fibers—think organic cotton, hemp, or tencel–the result is a new wave of sustainable fabrics that are both stylish and responsible.

5. Conclusion

Denim production has a huge carbon footprint as energy-intensive, low-efficiency, and wasteful use of water and chemicals has to occur for each step of the denim production process - from growing cotton (and all of the growing, fertilizers, and pesticides needed), dyeing, finishing, and distribution. Denim uses many hazardous chemicals at all stages such as sodium hypochlorite, potassium permanganate, and synthetic indigo dyes that may pollute streams, lakes, and aquifers, and that will harm workers and communities. Additionally, methods of production that include sandblasting or stone washing to give jeans distressed finishes can be so unsafe that workers are left with respiratory diseases such as silicosis that are not regulated in denim factories. Conversely, effluents produced from textile manufacturing waste directed into contaminated streams are disposed of without regulation to water bodies, causing harm to water creatures and ecosystems. Because of these issues, the industry is switching to more sustainable practices. Alternatives exist, such as laser finishing, ozone fading, and nanobubble treatments, which will dramatically decrease the use of water, energy, and hazardous emissions. Organic and recycled cotton, low-impact dyes, and waterless dyeing technology are also growing to become preferred alternatives in order to support sustainability. Brands are pivoting toward circular models, promoting denim recycling and repair to maximise product use cycles. Production planning is also being optimised using digital technologies to reduce waste and carbon emissions. However, despite these technological advances, deployment is slow owing to the high cost and technological complexities, especially in developing economies. Incorporating sustainable alternatives provides an effective solution for reducing the environmental and health risks of denim production. The future of denim is innovation that is people and planet-centric.

Compliance with ethical standards

Disclosure of conflict of interest

The authors have no conflicts of interest to disclose.

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