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GREEN INNOVATIONS IN SUSTAINABLE TEXTILE PROCESSING

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ABSTRACT

Green chemistry is a revolutionary approach that centers around creating products and processes with as few or negligible hazardous materials as possible. It emphasizes sustainability and environmental safety more than traditional chemistry, which frequently focuses on product yield and cost efficiency. This change is essential to solve the growing issues related to pollution and resource depletion. The textile industry, a significant contributor to environmental pollution, faces increasing pressure to adopt sustainable practices. This review explores and examines applications of green chemistry principles in textile production, including water-based processes, bio-based materials, and energy-efficient technologies. The review analyzes challenges such as cost implications, scalability and resistance to change within the industry. Emerging trends like closed-loop systems, advanced waste treatment methods, and smart textiles are discussed. It also evaluates strategies for implementing green chemistry, focusing on policy interventions, industry collaborations, and consumer awareness. Finally, it assesses the potential impact of green chemistry on reducing the textile industry's environmental footprint and promoting sustainable development. The findings suggest that while significant progress has been made, further research and innovation are needed to fully realize the potential of green chemistry in textiles.

Keywords: Bio-based materials, Chemical recycling, Energy-efficient techniques, Environmental footprint, Sustainable development

1. INTRODUCTION

Green chemistry is a scientific approach that emphasizes the design of products and processes that minimize environmental effects and increase sustainability. It is often used interchangeably with sustainable chemistry[1]. This approach is grounded in principles that prioritize waste prevention, the use of renewable feedstocks, and the reduction of toxicity[2]. Green chemistry is a critical component of sustainable chemistry, but it is not the only aspect; sustainable chemistry also considers economic and ethical dimensions throughout the lifecycle of chemical products[3]. Despite the progress, challenges remain, such as the full integration of biotechnological processes with green chemistry innovations. The principles of green chemistry are not only guiding the development of new chemical methodologies but also enhancing the sustainability of existing ones, contributing to the achievement of global sustainability goals [4]. The continued evolution and application of green chemistry are essential for addressing environmental challenges and promoting a sustainable future. Green chemistry plays a pivotal role in enhancing the sustainability of industrial processes by promoting environmentally friendly practices that minimize waste and reduce the use of hazardous substances. This approach not only addresses environmental challenges but also supports economic viability and social responsibility.This article explores how green chemistry principles and innovations can help reduce the environmental impact of chemical processes and promote sustainable practices across industries. It highlights the Twelve Principles of Green Chemistry, which aim to minimize waste and hazardous substances, as well as innovative approaches that improve industrial sustainability. The integration of closed-loop systems in the textile industry is discussed to show how products can have extended lifespans, reduced waste, and more efficient use of water and energy. Finally, the article addresses the importance of policy measures, industry collaboration, and consumer awareness to support responsible consumption and advance green chemistry practices.

The principles of green chemistry are essential for transforming textile wet processing into a more sustainable practice. These principles aim to minimize environmental impact by reducing waste, energy consumption, and the use of hazardous substances. The following sections outline the key aspects of these principles as applied to textile wet processing. The twelve principles of green chemistry serve as a framework for designing chemical processes that minimize environmental impact and enhance safety. These principles guide chemists in creating sustainable practices that reduce hazardous substances and promote efficiency.

A. Overview of the Twelve Principles

1. **Prevention of Waste**: Minimize waste generation at the source. Focuses on preventing waste rather than treating or cleaning up waste after it is formed. In textiles, this can involve optimizing processes to minimize chemical and water usage [5].
2. **Atom Economy**: Maximize the incorporation of all materials used in the process into the final product For textiles, this principle encourages efficient use of dyes and finishing chemicals.

3. **Less Hazardous Chemical Syntheses**: Designs synthetic methods to use and generate substances with little or no toxicity to human health and the environment. This principle promotes the use of safer dyes and processing chemicals in textile production[6].
4. **Safer Chemicals:** Design chemical products to be effective yet non-toxic Aims to design chemical products that are fully effective yet have little or no toxicity. In textiles, this could involve developing biodegradable dyes and finishes [7]
5. **Safer Solvents and Auxiliaries:** Minimize the use of solvents, where possible For textiles, this means replacing harmful solvents with water-based or bio-based alternatives in dyeing and finishing processes [8]
6. **Energy Efficiency:** Reduce energy requirements Minimizes energy requirements in chemical processes. In textile production, this could involve using low-temperature dyeing methods or energy-efficient machinery [9]
7. **Renewable Feedstocks:** Use renewable rather than depleting resourcesPromotes the use of renewable raw materials. This principle encourages the use of natural fibers or bio-based synthetic fibers in textile production.
8. **Reduce Derivatives:** Minimize the use of auxiliary substances In textiles, this could mean developing direct dyeing methods that require fewer chemical modifications.
9. **Catalysis**: Use catalytic reagents to enhance reaction efficiency. For textiles, catalytic bleaching or enzymatic treatments could be employed to reduce chemical usage.
10. **Design for Degradation**: Ensure that chemical products break down into innocuous degradation products, This principle promotes the development of biodegradable textiles and finishes.
11. **Real-time Analysis for Pollution Preventi**on: Develop analytical methodologies to allow for real-time monitoring. Develop analytical methodologies to allow for real-time, in-process monitoring and control. In textile production, this could involve implementing sensors for precise chemical dosing and process control.
12. **Inherently Safer Chemistry for Accident Prevention:** Design processes to minimize the potential for chemical accidents. Chooses substances and forms of substances to minimize the potential for chemical accidents. This principle encourages the use of safer alternatives to hazardous chemicals in textile processing [10]

B. Green chemistry innovations

Green chemistry innovations have significantly contributed to reducing pollution in the textile industry through various sustainable practices. Notable examples include:

1. Waterless textile wet processing advance Technique: - The advancement of waterless textile wet processing techniques is crucial for enhancing sustainability in the textile industry, which is notorious for its high water consumption and pollution. Recent innovations focus on methods that eliminate or significantly reduce water usage while maintaining efficiency and effectiveness in dyeing and finishing processes.

(i) Supercritical CO_2 Dyeing

Traditional dyeing processes use vast amounts of water and generate contaminated wastewater. Supercritical g(scCO2) dyeing is an innovative, eco-friendly alternative to traditional textile dyeing methods, significantly reducing water and chemical usage. This technique utilizes scCO2 as a solvent, allowing for efficient dyeing processes of polyester and blend of polyester fabrics Supercritical carbon dioxide (CO_2) dyeing replaces water with CO_2 in its supercritical state, which acts as a solvent for dye. The CO_2 is easily recycled, and no water is needed. This process reduces water usage by 100% and cuts chemical use by 50%. Companies like DyeCoo have commercialized this technology, contributing to significant environmental benefits[11].

Advantages of Supercritical CO2 Dyeing

- **Environmental Benefits**: scCO2 dyeing minimizes water consumption and eliminates harmful effluents, addressing the pollution issues associated with conventional dyeing methods.
- **Enhanced Dyeing Quality**: Studies show that fabrics dyed with scCO2 exhibit vibrant colors and improved wash and light resistance compared to traditional methods.
- **Efficiency**: The process allows for rapid dyeing with reduced energy expenditure, and the ability to recycle CO2 contributes to lower greenhouse gas emissions.

Even though scCO2 dyeing has many benefits, there are still issues with scaling the technique for large-scale industrial use. As a result, more research and development are required to guarantee economic viability and optimize procedures [12].

(ii) Air dyeing: Air dyeing represents a significant advancement in green technology within the textile industry, addressing the critical issues of water consumption and environmental pollution associated with traditional dyeing methods. This innovative technique utilizes air as a medium for dye application, drastically reducing water usage and harmful waste production. Air-dye technology applies color to textiles without the use of water or with a liquor ratio that is around 90% lower. Up to 95% less water and up to 86% less energy is used when using Air-Dye, which reduces global warming by 84% [13]. Since airflow is the best possible transmission medium, it is an essential part of this technique. By using air instead of colored liquid to transport the items, jet dyeing machines drastically reduce the amount of chemicals and water needed. The moisture-saturated airflow makes sure that the temperature is dispersed for consistent and dependable killing.

(iii) Plasma Technology: Plasma technology is emerging as a sustainable alternative in textile wet processing, addressing significant environmental concerns associated with traditional methods. This innovative approach minimizes water usage, chemical waste, and energy consumption, aligning with green technology principles. By changing a fabric's surface without changing its bulk qualities, this creative solution addresses environmental issues related to conventional dyeing techniques while enhancing colors and dye absorption, generating active sites on fabric surfaces, plasma treatment improves dye compatibility[14]. It makes it easier to apply nanomaterials as a pretreatment step. According to studies, plasma treatment can greatly increase the dyeability of a variety of materials, including polyester, cotton, and wool, and it provides a sustainable substitute for traditional dyeing methods[15]. Inducing surface modifications and improving textile material properties for enhanced dyeing rates, color enhancement, coated dye adhesion, and diffusion are the main uses of plasma technology. Plasma is activated following the coloring of the textile material inside the chamber. The particles engage with the surface of the textile material after they are formed. The surface of the material is structured into a functional group and forms a thin film with a thickness of one nanometer [16]. One of the advantages of plasma dyeing is that it produces vibrant, long-lasting color with little chemical and water outflow. The vibrant, long-lasting color produced by plasma dyeing has the advantage of requiring less chemical or water outflow. This method alters the exterior of the fiber instead of the material's inner. There is very little environmental impact. It does, however, also have certain drawbacks. Hazardous gases such as ozone and nitrogen oxides are released during the operation of this therapy. The plasma device is costly and requires an operator with a high level of expertise[17].

2. Bio-based Textile Colorants: The overuse of synthetic dyes upsets the balance of the environment by releasing unfixed colorants during production and application and creating significant volumes of hazardous waste. Natural colorants are becoming more and more popular because of their vast availability and variety of tones, which is in line with growing environmental concerns. Currently, research is concentrated on creating eco-friendly and sustainable products [18]. Natural dyes can produce subtle, subdued colors as well as creative traits. In active textile substrates, these properties could include UV protection, deodorizing, antioxidant, antibacterial, and antifeedant properties. Using natural colorants to create colorful textile items could boost consumer interest in today's market. Replacing natural dyes with biodegradable alternatives has been a primary priority for the industry. In textile coloring, a variety of plants and agricultural waste materials have shown promising results that are becoming more sustainable and eco-friendlier. Natural dyes are pigments made from plants, fungi, insects, invertebrates, or minerals. The majority of natural dyes are composed of vegetable colors, which are mostly made from various plant parts such roots, stems, seeds, bark, leaves, and wood. Additional biological sources, such as fungi, snails, and insects, are employed as textile coloring agents[19]. Natural earth pigments with tinctorial properties, such as oxides or hydrated manganese oxides, are the basis for mineral dyes. Manganese brown, Prussian blue, iron buff, nankin yellow, and chrome yellow are examples of mineral dyes [20].

Bioremediation Technology-Bioremediation technology utilizes biological processes to detoxify and restore polluted environments, offering a sustainable alternative to traditional remediation methods. This approach employs various organisms, including microbes, plants, and fungi, to break down harmful pollutants in soil and water[21]

Key Techniques in Bioremediation

- **Microbial Bioremediation**: Utilizes bacteria and fungi to degrade contaminants like hydrocarbons and heavy metals. For instance, specific bacterial species can effectively address oil spills[21], [22]
- **Phytoremediation**: Involves using plants to absorb and detoxify pollutants from the soil.
- **Hydrogel Applications**: Biobased hydrogels have been developed for dye removal from wastewater, achieving high removal efficiencies and demonstrating biodegradability.
- **Mycoremediation**: Employs fungi to break down complex organic pollutants.

Bioremediation is cost-effective, environmentally friendly, and can be applied in situ, minimizing disruption. Issues such as biological specificity, environmental variability, and regulatory hurdles can hinder its effectiveness. Despite its promise, bioremediation faces challenges that necessitate ongoing research and innovation to enhance its application and efficiency in diverse environmental contexts [23].

3. Enzymatic Textile Processing- Enzymatic textile processing is emerging as a sustainable alternative to conventional methods, significantly reducing environmental impact. This approach utilizes various enzymes, such as laccase, cellulase, and protease, to enhance textile processing while minimizing harmful chemical use and energy consumption. Enzymatic textile processing is emerging as a green alternative to traditional chemical methods, significantly reducing environmental impact while enhancing product quality. Enzymes such as amylase, cellulase, laccase, and protease are increasingly utilized across various stages of textile manufacturing, from desizing to dyeing and finishing [24].

Key Enzymes and Their Applications

- **Amylase**: Effective in removing starch impurities, improving fabric wettability.
- **Cellulase**: Used for bio-polishing and enhancing the appearance of denim and knit.
- **Laccase**: Facilitates dyeing processes, allowing for the use of natural dyes and reducing reliance on synthetic chemicals.
- **Protease and Pectinase**: Contribute to fabric softening and color enhancement.

Enzymatic processes are eco-friendly, leading to lower water and energy consumption. They minimize the release of toxic effluents, addressing significant environmental concerns associated with traditional textile processing[25]

While enzymatic processing offers numerous advantages, challenges remain, such as optimizing operational conditions for industrial scalability. Nonetheless, the shift towards enzymatic methods represents a promising direction for sustainable textile manufacturing.

4. Low-Impact Wet Processing Chemicals:- these are a key innovation in Green textile manufacturing, aimed at reducing the environmental harm caused by conventional wet processing methods. These methods typically involve various stages like scouring, bleaching, dyeing, and finishing, all of which can generate large amounts of toxic wastewater and require significant energy and water consumption. By using low-impact chemicals, the industry can decrease its environmental footprint while still achieving high-quality textile production, Green techniques bring revolutionary advances to the textile industry by taking environmental considerations into account. The textile industry's commitment to ecologically conscious practices is demonstrated by the latest advancements in various processing techniques [26].

Some of the products are as below

(i) Biodegradable Surfactants and Detergents:- Bio-based, biodegradable surfactants, such as those derived from plant-based oils (e.g., coconut or palm oil), provide a safer alternative. These biosurfactants exhibit diverse functions such as reducing surface tension, emulsifying hydrophobic compounds, and enhancing biodegradation processes. The biosurfactants are produced by microorganisms through a complex biosynthesis process. They combine green chemistry with a reduced carbon footprint, making them environmentally beneficial. They exhibit low ecotoxicity and are biodegradable, in natural environments and reduce impact on aquatic ecosystems. These biosurfactants exhibit diverse functions such as reducing surface tension, emulsifying hydrophobic compounds, and enhancing biodegradation processes. In recent years, there has been a growing interest in utilizing microbial biosurfactants in environmental applications[27]

(ii) Certified Chemicals : Certifications in the textile industry ensure safety for consumers, manufacturers, and the environment. They include standards for sustainable practices, such as water conservation and eco-friendly production processes[28].

Certifications in textiles include European Union Ecolabel, Oeko-Tex 100, Bluesign, Global Organic Textile Standard, Organic Content Standard, Fairtrade, Clear to Wear, and Ecosafe, Greenscree, ZDHC, focusing on sustainability and consumer demands[29]

The integration of green chemistry in textile processing is essential for reducing environmental impact and enhancing sustainability. ertifications provide credible evidence that products adhere to sustainability standards, influencing consumer purchasing decisions. The demand for certifications in textiles is rising, although challenges remain in aligning production with consumer expectations[30]

While certifications are essential for promoting sustainable practices, the gap between eco-label growth and consumer demand raises questions about their effectiveness in driving widespread adoption in the textile industry.This approach focuses on developing eco-friendly alternatives to traditional chemical processes, which are often harmful to both health and the environment. Various low-impact chemicals, such as non-toxic solvents and safe finishing agents, have been developed to replace traditional hazardous chemicals. Greenscreen certified chemicals are Less toxic to workers and consumers, Reduced risk of environmental contamination, Improved sustainability profile of the production process [31]. Various eco-friendly chemicals which substitute convectional hazardous chemicals like soda substitute, acid substitute, urea substitute represents a significant step toward a more sustainable and less polluting industry. These innovations help reduce chemical toxicity, water and energy consumption, and the overall environmental footprint of textile manufacturing.

5. Closed Loop System: -In the textile sector, the idea of closed-loop systems is essential for advancing sustainability and minimizing environmental effects. Through efficient textile recycling, these systems seek to reduce waste and resource consumption over the whole product lifecycle. Unlike the traditional linear system ("take-make-dispose"), closed-loop systems aim to keep textile materials in continuous circulation, minimizing the use of virgin resources and reducing pollution.

(i) Recycling and Upcycling Fibers: - Textile production generates significant waste, contributing to landfill overflows and microfiber pollution. Recycling and upcycling fibers in textiles represent innovative approaches to achieving sustainability in the fashion industry. These methods not only reduce waste but also create new materials that align with eco-friendly practices. Regenerated fibers, such as rayon and lyocell, are produced from low-value sources, enhancing sustainability by utilizing textile waste. These fibers exhibit favorable mechanical properties and biodegradability, making them suitable for mass production in green textiles.

Upcycling processes, like converting recycled polyethylene terephthalate (r-PET) into thermoplastic polyester elastomers (TPEE), demonstrate the potential for creating durable and flexible fabrics. This method not only addresses plastic waste but also enhances the mechanical properties of the resulting fibers (Ho et al., 2024). While these advancements are promising, challenges remain in effectively separating natural from synthetic fibers and ensuring the environmental impacts of production processes are minimized [4], [32].

(ii) Circular Product Design for Closed-Loop Textiles To support closed-loop systems, textile products must be designed with the entire lifecycle in mind, making them easier to recycle or biodegrade at the end of their use.

a) Design for Disassembly- Garments are designed to be easily disassembled into individual components (zippers, buttons, fabrics) to be recycled more efficiently. Example: Eileen Fisher incorporates this principle into its product line, designing clothing that can be easily taken apart and recycled or upcycled.

b) Monomaterial Design- Garments made from a single material (monomaterial) are easier to recycle because there are no mixed fibers that complicate the process. Example: Adidas's Futurecraft Loop shoe is made entirely from one type of plastic (thermoplastic polyurethane), allowing the shoe to be fully recycled into new shoes without separating different materials.

c) Modular Clothing: Modular clothing allows consumers to replace or upgrade parts of a garment (such as sleeves or pockets) without discarding the entire item. This reduces waste and extends the product's lifespan. Example: Rapanui and other sustainable brands design garments with modular components that can be easily swapped or repaired, fitting into the closed-loop ethos.

iii)Industrial Symbiosis in Closed-Loop Systems: -Closed-loop textile systems benefit from industrial symbiosis, where one company's waste is another's raw material. This collaborative approach optimizes resource use across industries.

a) Textile-to-Textile Recycling- Textile manufacturers can partner with recycling facilities to collect and process old garments into new textiles, creating a circular supply chain. Example: Teijin, a Japanese chemical company, uses polyester recycling technology to recover and recycle used polyester garments, turning them into new textiles for clothing and industrial applications.

b) Cross-Industry Waste Repurposing- Waste from other industries can be used as inputs for textile production. For instance, food industry waste (such as orange peels or milk) is being repurposed into biodegradable textiles.[30]. Example: Orange Fiber creates textiles from citrus juice byproducts, while MiTerro converts milk waste into biodegradable fibers.

6. Policy interventions, industry collaborations, and consumer awareness

Green chemistry is a crucial approach to reducing environmental harm and improving sustainability in industries, including textiles, pharmaceuticals, agriculture, and manufacturing. To successfully integrate green chemistry principles, collaboration across various sectors is essential. This includes government policy interventions, industry collaborations, and increasing consumer awareness. Here's how each aspect contributes to the growth and adoption of green chemistry. Policy interventions are essential for driving the adoption of green chemistry across industries by providing regulatory frameworks, incentives, and setting sustainability goals.

Key Policy Strategies: Governments can establish regulations limiting or banning hazardous chemicals and promoting safer alternatives. For example, the European Union's REACH Regulation (Registration, Evaluation, Authorisation, and Restriction of Chemicals) enforces strict control over chemicals in manufacturing, pushing industries toward green chemistry solutions. California's Safer Consumer Products regulation promotes the use of non-toxic alternatives by requiring manufacturers to find safer replacements for hazardous substances. Financial incentives, tax credits, or subsidies can encourage companies to invest in green chemistry research and development. Programs like the U.S.

Environmental Protection Agency's (EPA) Green Chemistry Challenge Awards reward companies that make significant strides in developing sustainable chemical processes. Research funding and grants can be provided to universities and institutions working on green chemistry innovations, helping accelerate scientific breakthroughs. Various countries have implemented strategies that emphasize education, regulation, and innovation to foster the adoption of green chemistry principles. In Spain, organized academic programs have successfully attracted students to green chemistry, highlighting the importance of education in fostering a skilled workforce[33].

The U.S. has also focused on optimizing the Twelve Principles of Green Chemistry, encouraging educational institutions to integrate these principles into their curricular[34].In the U.S., the revised Toxic Substances Control Act (TSCA) promotes the use of advanced testing methods to ensure safer chemical practices[35]. Countries like Germany and France have adopted policies to support green hydrogen development, showcasing a model that combines demand and supply-side interventions to enhance sustainability in energy and chemical sectors[36]. Policies that require producers to be responsible for the end-of-life management of their products encourage them to adopt safer and recyclable materials. This policy drives industries toward closed-loop manufacturing and greener alternatives. Policy frameworks like the Stockholm Convention on Persistent Organic Pollutants (POPs) have established global agreements to ban or restrict the production and use of highly toxic chemicals. Such bans motivate industries to adopt safer chemical processes. Bans on Toxic chemicals, Reduces the use of hazardous chemicals, Encourages the development of sustainable alternatives, Ensures compliance with environmental goals and international agreements. While these interventions are promising, challenges remain in harmonizing regulations and ensuring widespread adoption across different sectors.

2. CONCLUSION

Green chemistry represents a transformative approach within the chemical sciences, aiming to create products and processes that are inherently safer and more environmentally friendly. It is an integral part of the broader sustainable chemistry framework, which also encompasses economic and ethical considerations.

In summary, green chemistry represents a shift towards more environmentally responsible chemical research and engineering, with a focus on sustainability and the reduction of harmful impacts. Green chemistry innovations have significantly contributed to reducing pollution in the textile industry through various sustainable practices

These innovations demonstrate the potential of green chemistry to reduce the environmental impact of the textile industry by conserving water, reducing hazardous chemicals, and improving energy efficiency.These innovations contribute to reducing pollution and toxicity in textile applications by:

1. Minimizing chemical usage and waste generation
2. Promoting the use of safer, less toxic alternatives
3. Encouraging energy efficiency and resource conservation
4. Supporting the development of biodegradable and sustainable materials
5. Improving process efficiency and control
6. Reducing the risk of chemical accidents and environmental contamination
7. Promoting the use of renewable resources
8. Encouraging the design of safer products and processes from the outset

the textile industry can significantly reduce its environmental impact, minimize health risks to workers and consumers, and move towards more sustainable and green production practices.

3. REFERENCES

[1] [1] D. Pleissner and K. Kümmerer, "Green Chemistry and Its Contribution to Industrial Biotechnology," 2018, pp. 281–298. doi: 10.1007/10_2018_73.

[2] [2] S. D. Jain, A. Awasthi, and A. K. Gupta, "Green Chemistry: A Sustainable Path to Environmental Responsibility and Innovation," Asian Journal of Research in Pharmaceutical Sciences, pp. 51–55, Mar. 2024, doi: 10.52711/2231-5659.2024.00008.

[3] [3] N. Farhana et al., "Fundamental Principles to Address Green Chemistry and Green Engineering for Sustainable Future," in Green Chemistry - New Perspectives, IntechOpen, 2022. doi: 10.5772/intechopen.104717.

[4] [4] T. Kim, D. Kim, and Y. Park, "Recent progress in regenerated fibers for 'green' textile products," J Clean Prod, vol. 376, p. 134226, Nov. 2022, doi: 10.1016/j.jclepro.2022.134226.

[5] [5] R. B. Sharma, A. Kaur, U. Nautiyal, A. Kabra, and V. Arora, "The role of green chemistry and nanotechnology in developing environmental sustainability," in Role of Green Chemistry in Ecosystem

Restoration to Achieve Environmental Sustainability, Elsevier, 2024, pp. 33–40. doi: 10.1016/B978-0-443-15291-7.00009-2.

[6] [6] E. J. Lenardão, R. A. Freitag, M. J. Dabdoub, A. C. F. Batista, and C. da C. Silveira, "'Green chemistry': os 12 princípios da química verde e sua inserção nas atividades de ensino e pesquisa," Quim Nova, vol. 26, no. 1, pp. 123–129, Jan. 2003, doi: 10.1590/S0100-40422003000100020.

[7] [7] Sharma. , T. Bansal. , Radhika. , S. Kaur. Suvasini, "Green Chemistry: An Overview. Asian Journal of Research in Chemistry, ".

[8] [8] G. Hanrahan, "Green Chemistry and Sustainable Chemical Processes," in Key Concepts in Environmental Chemistry, Elsevier, 2012, pp. 297–319. doi: 10.1016/B978-0-12-374993-2.10010-X.

[9] [9] A.-Mohammed. , A. Q. Ali. , A. O. Wanisa, "Green Chemistry: Principles, Applications, and Disadvantages," Chemical Methodologies, vol. 4, no. 4, pp. 408–423, Jun. 2020, doi: 10.33945/SAMI/CHEMM.2020.4.4.

[10] [10] G. , Jessop. , S. Trakhtenberg. , J. C. , Warner. Philip, The Twelve Principles of Green Chemistry. .

[11] [11] C. R. S. de Oliveira, P. V. de Oliveira, L. Pellenz, C. R. L. de Aguiar, and A. H. da Silva Júnior, "Supercritical fluid technology as a sustainable alternative method for textile dyeing: An approach on waste, energy, and CO2 emission reduction," Journal of Environmental Sciences, vol. 140, pp. 123–145, Jun. 2024, doi: 10.1016/j.jes.2023.06.007.

[12] [12] K. Schmidt-Przewozna and E. Rój, "Green Sustainable Textile Supercritical Dyeing Process Using CO 2 Madder (Rubia t inctorum L.) Extract," Journal of Natural Fibers, vol. 20, no. 2, Nov. 2023, doi: 10.1080/15440478.2023.2277836.

[13] [13] Ms. S. (2), Mr. K. V. L. Mr. Vignesh Dhanabalan (1), " Air-Dyeing Technology-A Review,Textile Today,oct 14, 2015".

[14] [14] M. Kamel, "Development of Dyeing Reactive Dyes on Blended Banana Fabrics Treated with Plasma Technology," International Design Journal, vol. 13, no. 1, pp. 207–220, Jan. 2023, doi: 10.21608/idj.2023.276193.

[15] [15] M. Shakeri and A. Bashari, "Plasma Technology for Textile Coloration," in Emerging Technologies for Textile Coloration, Boca Raton: CRC Press, 2022, pp. 203–216. doi: 10.1201/9781003140467-12.

[16] [16] A. Carolina. paravigna, "Plasma treatments for textiles: an innovative technology for traditional and technical fabrics.. ".

[17] [17] Majid Sarmadi1, " Advantages and Disadvantages of Plasma Treatment of Textile Materials, 21st International Symposium on Plasma Chemistry (ISPC 21) Sunday 4 August – Friday 9 August 2013 Cairns Convention Centre, Queensland, Australia".

[18] [18] A. Panda, S. Maiti, P. Madiwale, and R. Adivarekar, "Natural Dyes—A Way Forward," in Textile Dyes and Pigments, Wiley, 2022, pp. 323–343. doi: 10.1002/9781119905332.ch16.

[19] [19] Md. Imran Hossain, " Sources and Applications of Natural Dyes, by Textile focus, 26 feb , 2021".

[20] [20] L. Chungkrang and S. Bhuyan, "Natural Dye Sources and its Applications in Textiles: A Brief Review," Int J Curr Microbiol Appl Sci, vol. 9, no. 10, pp. 261–269, Oct. 2020, doi: 10.20546/ijcmas.2020.910.034.

[21] [21] M. Saha, P. Chakraborty, and S. S. Roy, "BIOREMEDIATION: A REMEDY FOR ENVIRONMENTAL POLLUTION," in Futuristic Trends in Biotechnology Volume 3 Book 7, Iterative International Publishers, Selfypage Developers Pvt Ltd, 2024, pp. 276–305. doi: 10.58532/V3BDBT7P2CH3.

[22] [22] E. E. Lopéz-Martínez et al., "Hydrogels for Biomedicine Based on Semi-Interpenetrating Polymeric Networks of Collagen/Guar Gum: Synthesis and Physicochemical Characterization," Macromol Res, vol. 30, no. 6, pp. 375–383, Jun. 2022, doi: 10.1007/s13233-022-0047-3.

[23] [23] B. Mahanayak, "Environmental Restoration through Bioremediation: Methods, Advantages, and Challenges," International Journal of Research Publication and Reviews, vol. 5, no. 6, pp. 6661–6664, Jun. 2024, doi: 10.55248/gengpi.5.0624.1637.

[24] [24] Ms. Anju Kushwaha, Dr. Priyanka Kesarwani, and Rashi kushwaha, "ENZYMES USED FOR SUSTAINABLE WET PROCESSING IN TEXTILE INDUSTRY," international journal of engineering technology and management sciences, vol. 8, no. 1, pp. 276–283, 2024, doi: 10.46647/ijetms.2024.v08i01.036.

[25] S. Md. Mamun Kabir and J. Koh, "Sustainable Textile Processing by Enzyme Applications," in Biodegradation Technology of Organic and Inorganic Pollutants, IntechOpen, 2022. doi: 10.5772/intechopen.97198.

[26] A. B. V. R. S. S. & T. Arunraj, "Sustainable dyeing techniques: Advancements and innovations in the textile industry".

[27] A. Kashif et al., “Current advances in the classification, production, properties and applications of microbial biosurfactants – A critical review,” Adv Colloid Interface Sci, vol. 306, p. 102718, Aug. 2022, doi: 10.1016/j.cis.2022.102718.

[28] K. Amutha, “Sustainable Practices in Textile Industry: Standards and Certificates,” 2017, pp. 79–107. doi: 10.1007/978-981-10-2639-3_5.

[29] L. Almeida, “Ecolabels and Organic Certification for Textile Products,” 2015, pp. 175–196. doi: 10.1007/978-981-287-164-0_7.

[30] M. Falsafi, R. Fornasiero, and U. Dellepiane, “How to Make Industrial Symbiosis Profitable,” 2017, pp. 614–625. doi: 10.1007/978-3-319-65151-4_54.

[31] P. Pandit, S. Maiti, S. Maity, and K. Singha, “Green chemistry in textile processes,” in Green Chemistry for Sustainable Textiles, Elsevier, 2021, pp. 353–374. doi: 10.1016/B978-0-323-85204-3.00025-7.

[32] S. Bhandari, A. Agrwal, and M. Bhandari, “Approaches and challenges with respect to green chemistry in industries,” in Green Chemistry Approaches to Environmental Sustainability, Elsevier, 2024, pp. 93–107. doi: 10.1016/B978-0-443-18959-3.00015-X.

[33] R. Ciriminna, M. Formenti, C. Della Pina, R. Luque, and M. Pagliaro, “Green chemistry in Italy and Spain (1999–2019): Research policy lessons,” Sustain Chem Pharm, vol. 39, p. 101520, Jun. 2024, doi: 10.1016/j.scp.2024.101520.

[34] E. A. A. Jarvis, “Green chemistry in United States science policy,” Green Chem Lett Rev, vol. 12, no. 2, pp. 161–167, Apr. 2019, doi: 10.1080/17518253.2019.1609599.

[35] Faulkner. David, “Interventions to Encourage and Facilitate Greener Industrial Chemicals Selection. ”.

[36] A. Acharya, “Scaling-up Green Hydrogen Development with Effective Policy Interventions,” J Sustain Dev, vol. 15, no. 5, p. 135, Sep. 2022, doi: 10.5539/jsd.v15n5p135