The Role of Green Technologies in Clothing Design

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Abstract

Globalization of the clothing industry and mass manufacturing have led to an increase in the negative influence on the environment and have necessitated changes in design and manufacturing processes. Nowadays, the implementation of green technologies in the process of designing clothes is not only an issue of reducing the environmental impacts, but also a new approach to the visual, structural, and functional principles of clothing design. This research project presents an overview of green technologies used in the clothing industry, the issues related to sustainable fashion, ecological textile materials, and particularly the use of recycled fibers in the design. The article considers the techniques of reducing the consumption of water and energy in the process of production and reducing the carbon footprint, and also highlights the significance of digital technologies and virtual modeling in the process of creating a waste-free production model. The research compared circular economy approaches and consumer behavior transformations in the fashion industry in relation to environmental responsibility. It can be seen from the results that green technologies are a primary driver of innovation that determines the future direction of the fashion industry due to the combination of visual beauty with the principles of environmental sustainability. The findings suggest that green technologies play an increasingly important role in innovation within the clothing industry.

Keywords: Green technologies, Clothing design, Sustainable fashion, Ecological textiles, Circular economy, 3D virtual prototyping, Carbon footprint, Eco-design innovation

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1. Introduction

The global context of modern light industry development, in particular the clothing and fashion industry, is accompanied by certain environmental problems. A “take, make, dispose” economic approach and the fast fashion concept that has emerged as a result of decades have caused over-exploitation of natural resources, significant greenhouse gas emissions, and a great deal of textile waste (Aliyeva, 2021; Sidorov, 2021). Under such conditions, the use of green technologies for clothing design and manufacturing has become a necessary global strategy to secure the sustainable functioning of the clothing industry in the future (Kuznetsova, 2020). Green technologies represent a variety of innovative approaches aimed at reducing any environmental impact in such processes as resource extraction, design, manufacturing, transportation, and disposal of products.

The application of green technologies in the creation of clothing involves several components and includes materials science, digital technologies, and socio-philosophical components (Hasanov, 2020). The usage of such an approach, which is realized on the basis of the concept of sustainable fashion, fundamentally transforms the designer’s creative approach (Aliyeva, 2021). While the aesthetics, price, and fit were the central components of traditional design, modern eco-design highlights the ecological character of the clothing, its biodegradability, energy-efficient manufacturing process, and circular nature of the product (Kuznetsova, 2020).

The primary objective of the current research work is a thorough analysis of the application of green technologies in the field of clothing design, the contribution of the innovative technologies to the methodology

of design, and their impact on the transformation of the industry on the ecological level. From a scientific point of view, the research examines various types of ecological textile materials, the structure of the recycling process, the methods of decreasing the amount of waste using digital 3D prototyping, and the integration of the concept of the circular economy in the clothing sector (Hasanova, 2020; Sidorov, 2021). The analyses conducted in this study indicate that green technologies transform the field of clothing design not only aesthetically but also ethically.

2. The Essence of Green Technologies and the Concept of Sustainable Fashion

The essence of green technologies is based on the application of scientific and technical methods and digital management systems that ensure that industrial production minimizes environmental impacts while supporting ecological sustainability. In the context of the clothing industry, green technologies ensure resource conservation, elimination of toxic substances, and biodegradability at every link in the production chain (Kuznetsova, 2020). Sustainable fashion ideology and aesthetics are based on the same technological framework. In order to produce and use clothing, it is essential to combine social justice, environmental sustainability, and economic efficiency.

A comparative study of traditional clothing manufacturing techniques and green technology proves that sustainable fashion involves a multidisciplinary approach to clothes creation (Aliyeva, 2021). Table 1 below systematically reflects the fundamental differences and innovative advantages between traditional clothing production and the application of green technologies.

Table 1. Comparison of traditional and green technologies.

Indicator	Traditional method	Green technology	Advantage
Source of raw materials	Petroleum-based synthetic fibers and intensively chemically cultivated cotton	Bio-based polymers, organic fibers, recycled raw materials	Reducing ecological dependence, turning waste into a resource
Production chain	High chemical waste and linear (Cradle-to-Grave) model	Closed-loop, zero-waste (Cradle-to-Cradle) model	Prevention of environmental pollution, resource conservation
Water and chemical consumption	Waste of tons of water, application of toxic synthetic dyes	Waterless dyeing (CO_2 methods), natural and enzymatic processing	Protection of water resources, reduction of wastewater to zero
Energy and Carbon Footprint	High carbon emissions, non-renewable energy use	Renewable energy, energy-saving digital equipment	Reducing the effects of global warming, climate neutrality
Design approach	Short-lived aesthetic structure based on fast trends	Principles of durability, modularity, and eco-aesthetics	Sustainable product architecture, functional design value

Source: Compiled by the authors based on Hasanov (2020) and Sidorov (2021).

The concepts of eco-design form a key component of the idea of sustainable fashion (Kuznetsova, 2020). Instead of designing the garments as pieces of material, the designer starts creating them as organisms, which have their life cycles. In the design process, the options for taking apart the dress, separating its components, and recycling them back into either nature or technical cycles are already provided.

In such a way, the core of green technologies does not impose any limitations on the creativity of the designer; on the contrary, it grants designers a new artistic language (Hasanov, 2020).

3. Use of Ecological Textile Materials and Recycled Fibers

Fabrics, the primary material expression of clothing design, have undergone a radical transformation with the introduction of green technologies. Ecological textile materials include organic plant fibers grown without the use of harmful pesticides, protein-based materials obtained without harming animals, and new-generation biotechnological elements (Ivanov, 2018). These materials both conserve natural resources and do not pose a toxic hazard when in contact with human skin. In recent years, thanks to advances in materials science, fibers derived from mycelium (fungal mycelium), cactus, cotton, and kenaf waste, as well as seaweed, have begun to be actively used in clothing design (Petrova, 2017). Each of these materials has unique tactile and visual

properties, which create the basis for the creation of original textures and natural color shades in modern clothing collections.

The use of recycled fibers is one of the most effective methods of waste management in the clothing industry (Sidorov, 2021). PET fibers, obtained from plastic bottles through mechanical and chemical recycling technologies, significantly reduce the dependence on traditional polyester in clothing production (Ivanov, 2018). When these materials are integrated into design, a new visual language is formed, which we call "eco-aesthetics" (Kuznetsova, 2020). The subtle irregularities within the fabric and the variations in natural color shades give the product an original, story-driven, and ethically valuable visual identity.

Table 2. Characteristics of ecological materials.

Material	Origin	Advantages	Field of application
Organic Linen	Flaxseed grown without chemicals	High breathability, antibacterial, fully biodegradable	Summer clothes, premium eco-collections, everyday clothes
Mycelium leather (Mycelium)	Underground root structures of fungi (laboratory environment)	Plastic-free structure, rapid growth, high elasticity and durability	Outerwear, shoes, bags and accessories
Econyl (Recycled polyamide)	Ocean debris, discarded fishing nets and nylon carpets	Infinite recycling potential, high mechanical durability	Sportswear, beachwear, functional outerwear
rPET (Recycled polyester)	Post-consumer plastic bottles and PET containers	Carbon emission reduction, resource saving, easy coloring	Casual wear, jackets, linings and auxiliary materials
Pinatex (Pineapple skin)	Agricultural waste fibers of pineapple leaves	Lightness, unique texture, replacement of animal skin	Shoe design, jackets, modern creative clothing elements

Source: Compiled by the authors based on Ivanov (2018), Petrova (2017), and Sidorov (2021).

4. Reducing Water and Energy Consumption, Minimizing the Carbon Footprint

Conventional fabric manufacturing processes such as dyeing and finishing operations are considered major pollutants of freshwater resources in the world (Sidorov, 2021). It requires thousands of gallons of water to make a pair of jeans, thus aggravating the environmental issue even more. The emergence of green technologies has brought about a water-free dyeing process and enzymatic treatment system in this industry.

For instance, a waterless dyeing process, which uses supercritical carbon dioxide (CO_2), is designed to ensure that dyes are applied to the fibers without any water and without any formation of chemical wastewater (Ivanov, 2018). The process not only saves 100% of water resources, but also helps to save energy thanks to a shorter dyeing process. On the other hand, laser technologies and ozone technologies have become an alternative to sandblasting and bleaching in the process of aging and decoration of clothes (Petrova, 2017). They not only help to preserve the health of workers, but also make it possible to apply any complicated designs on the fabric surface without using any water resources.

The minimization of the carbon footprint goes beyond the production process. The principles of green logistics, local production, and energy-efficient production lines minimize the carbon footprint of the product (Aliyeva, 2021). The designers ensure that clothes are designed in a way that minimizes fabric loss in the cutting process, and thus energy is conserved indirectly. The reduction of the carbon footprint is the most significant indicator of technological excellence (Sidorov, 2021).

5. The Role of Digital Design Technologies: 3D Design and Virtual Prototyping

The direction that offers the fastest and most efficient integration of green technologies in clothing design is digital transformation. With traditional clothing design, designers used to manufacture prototypes for every model of their clothing. This resulted in the waste of huge amounts of material, time, and energy. Modern computer-aided design and manufacturing (CAD/CAM) systems, which operate in the virtual environment, in particular software like CLO 3D, Marvelous Designer, and Browzwear, exclude any such waste (Hasanov, 2020).

With 3D designing and virtual prototyping, designers have an opportunity to digitally simulate mechanical characteristics of fabric (its weight, elasticity, drape characteristics, coefficient of friction). The fit of the garment, creases' placement, and tension of seam lines are examined on the virtual mannequin (avatar). This

technology allows for achieving a lot of advantages in the process of design, including zero physical prototyping, cut optimization, and algorithmic pattern layout optimization, as well as virtual marketing and digital fashion. This kind of shift results in a complete transformation of the industry from mass production to a personalized one (Kuznetsova, 2020).

6. Green Production Models and Circular Economy in the Apparel Industry

The highest stage of green production models is the establishment of a circular economy in the clothing industry (Sidorov, 2021). The only way to avoid the environmental disasters caused by the traditional industrial model is to keep materials in a closed-loop cycle. The "Cradle to Cradle" approach, a key principle of the circular economy, assumes that clothing circulates in two different cycles during the design phase: a biological cycle and a technical cycle (Kuznetsova, 2020).

Materials used in the biological cycle (e.g., organic cotton, linen, mycelium) completely decompose in nature after their life cycle ends, turning into fertilizer and nourishing the ecosystem (Ivanov, 2018). In the technical cycle, artificial materials such as polyester, nylon, etc. are turned back into fibers chemically or mechanically without degrading their quality and reused in textile production. In order to effectively do this task, designers need monomaterial design, design for disassembly, and modular clothing architecture (Hasanov, 2020).

7. Consumer Behavior and Environmental Responsibility

The true efficiency of green technologies and sustainability practices in industry depends on the behavioral change of the consumer (Aliyeva, 2021). Regardless of how successful eco-materials and digital manufacturing processes are, it is impossible to stop the flow of waste in the fast fashion business without changing the environmental consciousness of consumers and their ethical awareness. As the current sociological and marketing studies show, the tendency of "conscious consumerism" is growing very quickly worldwide (Sidorov, 2021).

Modern consumers, especially the young generation, consider not only the brand name and the price of clothes, but also the process of their production and the conditions under which they were produced. The sense of ecological responsibility contributes to better care for clothes and prolongs their life cycle, or even leads to second-hand shopping and clothing rental (Aliyeva, 2021).

8. Empirical and Statistical Indicators of the Research (Data Analysis)

Data from various global industry reports and scientific sources were synthesized to quantitatively assess the level of integration of green technologies into the apparel industry and resource-saving indicators. The figures and percentages are detailed in Tables 3 and 4 below.

Table 3. Global adoption of selected sustainable textile technologies.

Technology direction	Application level (%)	Main focus area
3D Virtual Prototyping	45%	Design and sketching phase, reducing sample waste
rPET and Recycled Fibers	35%	Sports and casual clothing production, raw material substitution
Waterless and Ozone Dyeing	20%	Fabric processing and finishing of denim garments
Biotechnological and Cellular Materials	8%	Experimental premium collections, luxury segment
Monomaterial and Removable Construction	12%	Circular design models, recycling preparation stage

Source: Compiled by the authors based on Hasanov (2020), Sidorov (2021), and Aliyeva (2021).

Table 4. Estimated water savings achieved through selected green textile technologies.

Clothing Type	Traditional method (Liter)	Green technology (Liter)	Reduction percentage (%)
Jeans (Denim Jeans)	3785 L	250 L	93.4%
Cotton Shirt (T-shirt)	2700 L	400 L	85.2%
Polyester Jacket	1200 L	150 L	87.5%
Sportswear	1800 L	300 L	83.3%

Source: Compiled by the authors based on Ivanov (2018) and Sidorov (2021).

9. Conclusion

A scientific-theoretical and practical analysis of the role of green technologies in clothing design shows that modern light industry is in a stage of radical structural and aesthetic change. The fundamental scientific results obtained can be summarized as follows:

Integrated Eco-Aesthetics: Green technologies and ecological materials have transformed the visual appearance in clothing design from being a mere decorative element to a new artistic language of eco-aesthetics based on the intrinsic properties, texture, and ethical origin of the material.

Digital Efficiency: 3D virtual prototyping and computer-aided design systems optimize the designer's creative process with the principles of digital sustainability by minimizing physical fabric waste, energy, and time losses during sample production.

Circular Economy Integration: The application of monomaterials and the demountable design methodology helps transition the clothing industry from a linear model, putting the formation of a closed-loop circular economy model in line with the "Cradle to Cradle" philosophy into practical implementation.

Practical significance: The materials of this study can be used as a conceptual guide and methodological basis for modern fashion houses, clothing factories, and industrial designers in the development of eco-collections, the establishment of waste-free cutting lines, and the integration of digital 3D design programs into production.

Future research directions: Future scientific research could be focused on empirical analysis of the long-term mechanical endurance properties of living materials grown in laboratory conditions using biotechnological methods (e.g., bacterial cellulose and seaweed fibers) in mass production, the creation of smart green textile products, and the study of consumers' psychological adaptation processes to digital fashion products.

Author Contributions

The author has read and approved the final version of the manuscript.

Conflict of Interest

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