THE ROLE OF BIO-DESIGN IN RESTORING FASHION WITH A FOCUS ON WELL-BEING

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ETHICAL DECLARATION

I hereby declare that I am the sole author of this thesis and that I have conducted my work in accordance with academic rules and ethical behaviour at every stage from the planning of the thesis to its defence. I confirm that I have cited all ideas, information and findings that are not specific to my study, as required by the code of ethical behaviour, and that all statements not cited are my own.

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ABSTRACT

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Master's Program in Design Studies

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The current economic framework, based on anthropocentric imperatives, has led to significant ecological degradation. These concerns form the basis of circular design methodologies. Accordingly, there is an urgent need to find more circular and ecologically benign alternatives to fashion production and to re-evaluate individuals' enduring relationship with 'fashion'. In this context, bio-design is emerging as a transformative discipline emphasizing ethical and material practices in production, circularity, and implications for human and planetary well-being. Guided by a conceptual framework advocating a design methodology that collaborates with nature, this study explores the relationship between humans and nature through bio-design and how this relationship can contribute to well-being through textiles and garments that reconnect with ecological systems. As part of this study, a practical collaboration with the Sun Tekstil R&D Center aims to demonstrate how experimentally applied bio-design is seeking to find a space on an industrial scale through new textile and material innovations. A knitted fabric was produced using

SeaCell™, a seaweed-based fiber known for its antioxidant properties, dyed with green seaweed *(Ulva lactuca).* Following that, a garment was produced that embodies the principles of circularity and ecological well-being. Additionally, bioplastic material experiments were conducted with sea lettuce, a green seaweed species *(Ulva lactuca),* exploring potential applications in the fashion industry. These practical applications emphasize the potential of seaweed-based materials to contribute positively to human well-being and the ecosystem while offering the capacity to create a more circular fashion industry through cleaner production processes.

Keywords: circularity, bio-design, well-being, bio-based textiles, seaweed-based materials

ÖZET

MODANIN REFAH EKSENLİ İYİLEŞTİRİLMESİNDE BİYOTASARIMIN ROLÜ

Özbengi Uslu, Filiz

Tasarım Çalışmaları Yüksek Lisans Programı

Tez Danışmanı: Doç. Dr. Şölen Kipöz

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İnsan merkezli zorunluluklar üzerine kurulu mevcut ekonomik çerçeve, önemli ölçüde ekolojik bozulmaya yol açmıştır. Bu endişeler döngüsel tasarım metodolojilerinin temelini oluşturmaktadır. Buna göre, moda üretimine daha döngüsel ve ekolojik açıdan daha iyi huylu alternatifler bulmaya ve bireylerin 'moda' ile olan kalıcı ilişkisini yeniden değerlendirmeye acil ihtiyaç vardır. Bu bağlamda, biyo-tasarım, üretimde etik ve maddi uygulamaları, döngüselliği ve insan ve gezegenin refahı için çıkarımları vurgulayan dönüştürücü bir disiplin olarak ortaya çıkmaktadır. Doğayla işbirliği yapan bir tasarım metodolojisini savunan kavramsal bir çerçevenin rehberlik ettiği bu çalışma, biyo-tasarım yoluyla insan ve doğa arasındaki ilişkiyi ve bu ilişkinin ekolojik sistemlerle yeniden bağlantı kuran tekstil ve giysiler yoluyla refaha nasıl katkıda bulunabileceğini araştırmaktadır. Bu çalışmanın bir parçası olarak, Sun Tekstil Ar-Ge Merkezi ile yapılan uygulamalı bir işbirliği, deneysel olarak uygulanan biyo-tasarımın yeni tekstil ve malzeme inovasyonları yoluyla endüstriyel ölçekte nasıl yer bulmaya çalıştığını göstermeyi

amaçlamaktadır. Antioksidan özellikleriyle bilinen deniz yosunu bazlı bir elyaf olan SeaCell™ kullanılarak yeşil deniz yosunu *(Ulva lactuca)* ile boyanmış bir örme kumaş üretilmiştir. Bunu takiben, döngüsellik ve ekolojik refah ilkelerini bünyesinde barındıran bir giysi üretilmiştir. Ayrıca, yeşil bir deniz yosunu türü olan deniz marulu *(Ulva lactuca)* ile biyoplastik malzeme denemeleri gerçekleştirilerek moda endüstrisindeki potansiyel uygulamaları araştırılmıştır. Bu pratik uygulamalar, deniz yosunu bazlı malzemelerin insan refahına ve ekosisteme olumlu katkıda bulunma potansiyelini vurgularken, daha temiz üretim süreçleri yoluyla daha döngüsel bir moda endüstrisi yaratma kapasitesi sunmaktadır.

Anahtar Kelimeler: döngüsellik, biyotasarım, refah, biyo bazlı tekstiller, deniz yosunu bazlı malzemeler.

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CHAPTER 1: INTRODUCTION

1.1. Problem Statement

Processes such as textile manufacturing or the consumption-oriented model of fast fashion not only incorporate the attributes of their counterparts of the industry in question, such as jeopardizing the living conditions of minorities and indigenous communities, but also maintaining negative cycles of waste and pollution as well as furthering the causes of biodiversity depletion, thus prompting important questions about the fashion industry's involvement in the broader ecological crisis. The increasing study of the multiple impacts of the fashion industry has revealed the need to redesign and implement more circular, more humane, and more environmental alternatives to current material use and production processes. At the same time, there is a growing awareness of the imperative to address these needs in ways that contribute to both planetary and human well-being. This understanding arises from the interconnectedness of human and planetary well-being, highlighting the essential connection between our vitality and the overall well-being of the planet.

The concept of well-being is situated at the center of addressing the crises created by the fashion industry. Well-being involves a holistic view of human development that goes beyond mere physical health or economic prosperity and integrates mental, emotional, social, and environmental health. Well-being involves the need to rethink not only the object but also the production as it concerns lives. In the context of fashion, this means creating systems and products of clothing and textiles that not only do not harm but also benefit both the world in which these resources are produced and the environment in which the final products are sold and used. The concept of design can therefore be understood in terms of goals that are in harmony with design, and therefore design in itself is relevant to the global goals of sustainable management of quality of life.

When considering the relationship between design and well-being, various concepts emerge, including Desmet's idea of positive design, which is primarily centered on emotions and shaped by the expectations of an experience-oriented Western society (Desmet and Pohlmeyer, 2013). These include user-centered design approaches that

consider ergonomic factors and emotional involvement (Norman, 2004) or inclusive design principles that promote social equity (Clarkson and Coleman, 2015). In addition, Manzini's concept of social innovation in design suggests that design is not only about creating products, but also about enabling systems and mechanisms that lead to sustainable living and improved community well-being (Manzini, 2015). In biophilic design, which is an architectural approach, the positive effects on human health and emotional well-being have been emphasized (Sahu and Jha, 2021), as well as the psychological benefits of using natural materials have been discussed in the literature (Gillis and Gatersleben, 2015).

When considering the field of fashion design, the relationship with well-being is often associated with health and is discussed in the context of smart textiles (pain relieving, muscle relaxing, UV protection, etc.) (Jiang et al., 2021), wearable technologies (monitoring heart rate, blood pressure and sleep patterns, etc.) (George et al., 2023), and medical textiles (hydrogels, sewing threads, wound healing textiles, etc.) (Oliveira et al.,). The connection with well-being is also mediated in sustainable textiles, although in terms of a human-planet connection, it still cannot be viewed comprehensively enough. Sustainable textiles are skin-friendly due to their breathability and comfort, although they do not have healing properties, however, the selection of sustainable materials in textile production requires a close connection between environmental and individual well-being by covering many issues such as raw material harvesting, supply chain network, working conditions in this network, social justice in the period from the sourcing of the material until it becomes a product.

As sustainability discourses are increasingly replaced by circularity, new material trends are emerging and the source, production process and experience of these materials are also influencing the fashion industry. In line with the principles of ecological balance, bio-design promotes a design philosophy that mimics natural systems and processes (Myers and Antonelli, 2018) and is uniquely positioned at the intersection of science and technology to contribute to more applications for holistic well-being. The relevance for the fashion industry is about utilizing existing resources without creating new waste. The interest in bio-based resources, focusing on circularity from material selection to post-production, potentially could change

the relationship between designers and the materials they use and allow the material to be seen as part of a continuous loop, not just as a resource.

Bio-based textiles and bio-design applications in the fashion industry are emerging as a new area of interest and research. As stated in the s, the market size of bio-based materials has been determined as USD 41 billion. The market is projected to increase from USD 37 billion in 2023 to USD 203 billion in 2027. The market is expected to grow by 25 percent to reach 99 billion by 2030. This will be 60 percent in the period 2024-2030. A study also shows that the global bio-textiles market is expected to expand at a CAGR (compound annual growth rate) of 9.5 percent from 2022 to 2030 (Contrive Datum Insights, 2022). Bio-based textiles received the highest three biomaterial funding of 2022, indicating that the current market share is growing rapidly (World Bio Market Insights, 2022). As the market of bio-textiles develops some issues appear, including the questions of how to increase production, how to decrease costs, and how to make the supply chain more sustainable. Nonetheless, companies are never relenting in their effort to come up with solutions for these challenges so that these new materials can be made available to the fashion industry for use. And bio-design, the practice of designing products that mimic the way nature works, could provide a solution to the environmental harm done by the fashion industry through minimizing water usage, chemical inputs, and waste output.

In addition to the conventional bio-based materials such as cotton, linen, wool, silk, with the developments in the field of bio-design and technology, food waste such as banana, pineapple and orange peel, microbial-derived bacterial cellulose or mycelium with self-growth potential, algae and some seaweeds, which are considered to be of plant origin with their photosynthesis feature, have also become among the subjects invested especially by the major fashion companies (Common Objective, 2021; Morrow et al., 2023). Among these, seaweed, a marine biomass, is rich in vitamins, minerals, and antioxidants and has been used as food or for healing purposes in many cultures for hundreds of years (Salido et al., 2023). While seeking alternatives to traditional materials within the scope of circular design principles, seaweed emerges as a promising resource due to its abundant availability, rapid growth rate, and minimal ecological footprint. Seaweed has an advantage, in its renewability compared to materials like plastics. The material is biodegradable and

can be easily grown without requiring land, freshwater resources, or chemicals (Nakhate and van der Meer, 2021). This eco-friendly feature makes it a popular choice for purposes like packaging and construction materials. For instance, researchers are working on seaweed-based bioplastics to replace petroleum-based plastics addressing the issue of pollution (Lomartire et al., 2022). These bioplastics are applied in packaging, products, and even in certain electronic products. Seaweed use extends even in the textile industry. Seaweed fibers have characteristics like anti-bacterial, antioxidant, and anti-microbial practicality. Some of these properties recommend seaweed-based textiles for use in apparel, home textiles, and even in the medical sector (Janarthanan and Kumar, 2019).

On the other hand, major fashion companies support new initiatives such as AlgiKnit (now called Keel Labs) working together with H&M Group for pilot projects that may utilize the prototype fibers (World Bio Market Insights, 2022). Also, SeaCell™ fibers, which are extracted from Ascophyllum nodosum – among the brown seaweed species – have been slowly entering the edition of garments, underwear as well as bedding products in the commercial market. Hence the smooth, natural fiber provides added value to the textile industry as it is eco-friendly and also has traces of antioxidants to enhance the general well-being of the human body.

Increasing bio-design and circular fashion discussions and practices show a radical shift in the fashion system from being oppressive to humans and destructive to the environment to being biomimetic and restorative. The industry therefore has the potential to bring prosperity and solve some of the world's most pressing environmental and social problems through new uses of seaweed-based textiles. Thus, this research not only enriches the understanding of the concept of interdependence between human and environmental well-being but also provides experience in applying these principles to conventional fashion design approaches. With such new strategies, the fashion industry can move beyond being just an ordinary consumer product and become an advocate of ecological stability and improved human well-being.

Among the focus of this study, bio-design, well-being, fashion design and circularity, the research questions were specified as follows;

1. How does bio-design redefine the human-nature interface and can it serve as a medium for ecological restoration and human well-being?
2. How can fashion products be produced using bio-based textiles?
3. How can fashion industry adopt an integrated approach to material selection and innovation that benefits both human and environmental well-being?
4. How can seaweed-based materials contribute to the circularity of the fashion industry, especially when compared to conventional materials?

1.2. Aim and Scope of the Study

The problem of interest in this research is to define what bio-design means in the context of the fashion industry and the impact it has on humans and the environment. This research is based on the concept of circularity and focuses on seaweed-based fashion products as a healing artifact that helps to restore the human-environment relationship.

The scope includes an in-depth examination of current circular design methods, bio-design principles, and the changing human-nature relationship as a tool for ecological restoration and individual well-being. The study investigates the antioxidant properties of seaweed-based materials and their contribution to circularity in the literature.

This research aims to make a useful contribution to the literature by focusing on an unexplored research gap, specifically circular design strategies in the fashion industry. Whilst the current discourse mainly consists of issues that undermine the importance of nature, this research adopts a more inclusive framework that encompasses bio-design principles. Thus, this work provides a new point of view that takes into account both the environmental and the social aspects of sustainability. The antioxidant activity of seaweed-based products and the potential to expand the applicability of seaweed bio-based textiles and biomaterials in design are the primary contributions of the research. This study extends material innovation and acknowledges bio-design as an area that includes ethical, social, and well-being aspects.

1.3. Methodology

This study consists of several phases of data collection, analysis, and practical application to explore the potential of bio-design in transforming the fashion industry, focusing on the integration of seaweed-based materials such as SeaCell™ fiber and green seaweed (*Ulva lactuca).* This study employed a qualitative research methodology to examine the concept of well-being in the literature review, its equivalents in different disciplines, its relationship with the body and clothing, sustainable textiles, the relationship between circularity and well-being, and the relationship between the fashion industry and planetary boundaries. In addition, the relationship between bio-design and fashion has been reviewed, its relationship with circularity has been established and the gaps in its connection with well-being have been identified. In addition to literature research, the practical implementation and empirical study have been conducted in two parallel paths; the first one was the production of seaweed-based bioplastics, different natural dyeing trials with two different seaweed species, and the knitting of SeaCell™, a bio-based fiber, in collaboration with industry, sample design, pattern-making study, and sample production. Within the industrial part of the study, the practical applications of SeaCell™ fiber in fashion design on an industrial scale were investigated in collaboration with the R&D Center of Sun Tekstil, a ready-to-wear manufacturer and exporter company. This industry collaboration provided a promising opportunity to test the scalability and commercial viability of the prototype.

1.4. Limitations

There are some limitations that can influence the scope and feasibility of the findings in this study;

- There is variability in the production of bioplastics made from green seaweed (Ulva lactuca) due to raw material dependence and environmental variations in raw material quality and availability. The quality and performance of these materials may be subject to seasonal and environmental conditions, which could potentially impact the reproducibility of research outcomes and the scalability of production.

- As much as the cooperation with Sun Tekstil's R&D Center enables conducting production-scale experiments, implementing experiment outcomes on a small scale into large-scale production is still an issue. The utilization of novel bio-based textiles and bio-design in the industrial sector of fashion requires several technical and economic challenges which are not discussed in this research sufficiently.
- Dyeing and fabric production processes involving natural materials are subject to variations in experimental conditions that can affect the uniformity and comparability of results. Although efforts are being made to standardize these processes, it is difficult to achieve complete control, which may affect the validity of the findings.
- The study does not address the potential regulatory challenges associated with bringing new bio-based materials to market. Changes in environmental regulations, trade policies and industry standards could significantly impact the feasibility and timing of bio-design innovations in fashion.

Recognizing these limitations, the study aims to provide a realistic overview of the challenges in advancing bio-design in the fashion industry. Future research could focus on addressing these shortcomings and further develop the practical application and understanding of the role of bio-design in supporting ecological and human well-being.

1.5. Structure of the Study

The study consists of three main chapters: Well-being in Fashion, Emerging Role of Bio-design in Fashion Practice and Experience Space for a Bio-design Practice.
Following an introductory chapter that lays the groundwork for the whole study by highlighting the negative environmental and social impacts of current fashion industry practices, explaining the role of well-being between fashion design, bio-design, humans, and the ecosystem, Chapter 2: Well-being in Fashion provides an in-depth analysis of the concept of well-being in fashion practices. The chapter begins by considering the connection between human and ecosystem well-being, starting from the symbiotic relationship between human and planetary boundaries. Then, the chapter covers our relationship with the concept of well-being through the body and

clothing, the concept of well-being in design, and the historical evolution of the concept of well-being in fashion and clothing. In the same chapter, the connection between well-being and sustainable textiles, which are the most frequently encountered in the literature when the concept of well-being in fashion is considered, is analyzed in terms of sustainability and circularity, and the issues of where bio-based textiles stand and how much they respond to expectations are discussed.

Chapter 3: The Emerging Role of Bio-Design in Fashion Practice explores the link between bio-design and well-being, considering bio-design as a promising way forward. It questions the role of bio-design in circularity and explains the evolving position of fashion designers who are increasingly taking on the role of agents of positive change. This chapter also elaborates on current fashion bio-design for well-being.

Chapter 4: Experience Space for a Bio-Design Practice starts with explaining the decision-making process regarding the use of seaweed material and focuses on the positive impacts of health and circular economy. The following parts cover harvesting seaweed and developing seaweed-based materials, dye experiments, and documentation. Furthermore, through collaboration with industry, this chapter illustrates the process of using SeaCell™ fiber and its transformation from the design phase into a fashion product, including pattern-making and sewing. The chapter concludes by describing the process of creating a design system guided by bio-design principles and reshaping the role of the fashion designer in supporting circularity and ethical practices, as well as the designer as a collaborator designing with the material.

CHAPTER 2: WELL-BEING IN FASHION

This chapter focuses on well-being, exploring the new scenario where fashion and well-being meet. It reveals designers' transformative potential in shaping a circular and resilient future. This chapter includes an explanation of the concept of well-being and its implications for human beings and the planet we are living on, the different definitions in the academic literature, the engagement of the body and clothing when it comes to the human factor, how it is discussed in design and its historical role in fashion. It also includes where well-being can be positioned within the pace of the fashion industry. It concludes by considering the role of sustainable textiles in this context, including sustainability, circularity, and bio-based textiles.

2.1. Well-being Regarding Planetary Boundaries and Fashion Industry

It is undeniably evident that natural assets are no longer adequate to meet the demands of contemporary society due to factors such as burgeoning population growth, industrialization, and unsustainable exploitation. The success of industrial production upon handcrafted processes driven by the ease of scalability across all stages of production created the need for profitable business models specific to the currently dominant neoliberal and linear economic models (Upadhayay and Alqassimi, 2018).

Examples of the fashion industry’s environmental effects and the planetary crises it generates are visible at every level, including water pollution, the overconsumption of resources, and carbon footprint. However, by enhancing the fashion system, we can ensure that fashion is more sustainable as a system, leading to an improvement in planetary well-being. This potential for positive change should inspire us to redefine the concept of well-being in a way that encompasses planetary boundaries and identifies those that affect both people’s and the planet’s well-being negatively.

According to Steffen et al. (2013), planetary boundaries are based on the connectedness of human well-being and environmental integrity, arguing that staying within these boundaries can enhance and sustain human well-being. This concept is extended by Barañano et al. (2021), who propose a framework that combines ecological security with social justice and creates a practical space for human

activities. This framework aims to define a ‘safe operating space for humanity’ by integrating social justice issues with the physical limits of human-induced environmental changes (Rockström et al., 2009). This framework identifies six exceeded planetary boundaries: climate change, biosphere integrity, changes in land systems, changes in biochemical fluxes (mainly nitrogen and phosphorus), freshwater consumption, and ocean acidification. These boundary breakdowns indicate the severity of the ecological crisis and the urgent need for sustainable practices. Crossing any of these boundaries, primarily through multiple localized disruptions, could push parts of the Earth system into new situations potentially harmful to humans (Lade et al., 2019).

The planetary boundaries framework plays a vital role in measuring the impacts of our actions on the Earth system, as well as the actions of the fashion system, particularly in identifying critical ecological processes such as biodiversity loss. It is crucial to recognize that biodiversity loss results from various causes, including expanding supply chains to meet today’s growing consumption demand (Wilting et al., 2017). Indeed, existing frameworks often fail to address the ecological crisis and biodiversity loss in a way that links them to the fundamental goal of advancing equitable well-being

The environmental consequences of the fashion industry are undeniably severe, stressing the planet and contributing to environmental pollution and degradation in many ways. The extensive supply chain in the fashion industry has many negative impacts on water and energy usage, chemicals, pollution of water and air, waste, and microplastics. These impacts threaten planetary boundaries, directly impacting planetary well-being, and negatively affecting human well-being both socially and physically. However, by acknowledging our role in this, we can also recognize our power to make a positive change (Jacometti, 2019).

In fashion design and the fashion industry, the concept of well-being is frequently associated with advancing ethical and socially responsible practices during the entire garment manufacturing lifecycle. The threat of planetary boundaries is directly linked to the environmental degradation caused by the fashion industry; intersections are illustrated in Figure 1:

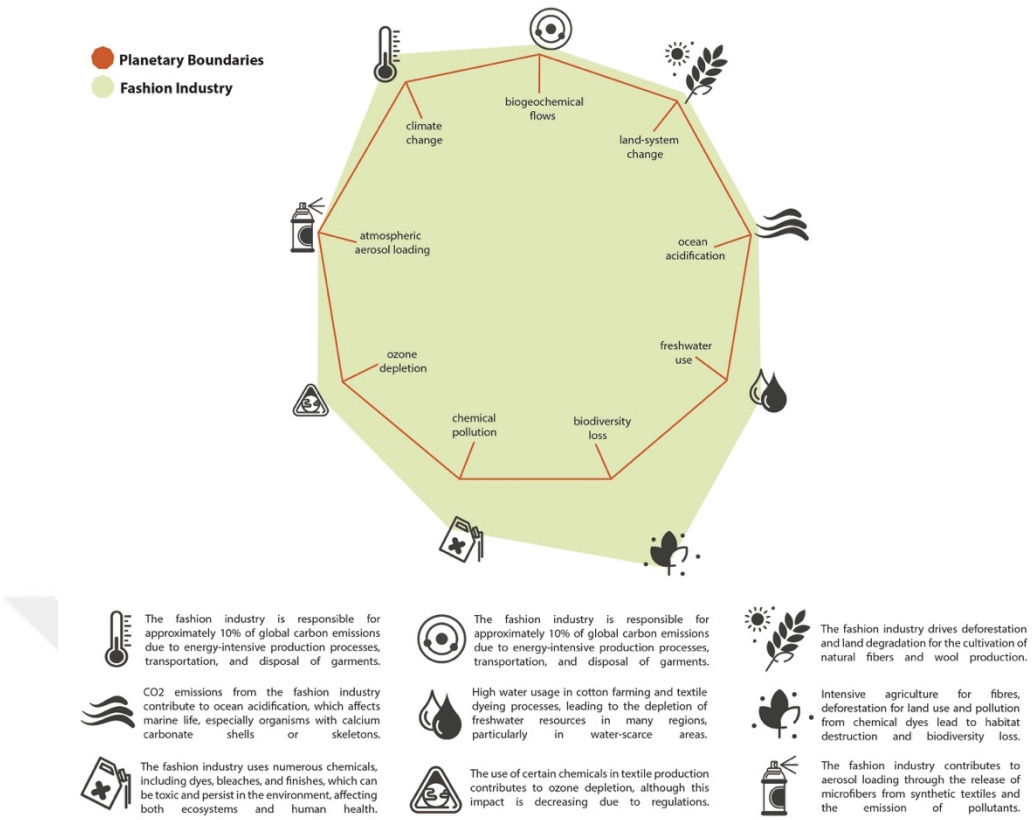

Figure 1. The intersection of planetary boundaries and the disruption caused by the fashion industry, illustrated based on information from Jacometti's study (2019)

The greenhouse gas emissions, use of pesticides, the release of microplastics with synthetic fabrics such as polyester, exploitation of fresh water, contribution to air pollution, and threatening biodiversity by disrupting the environment are quite significant in terms of the negative impact of the fashion industry on ecosystems and human societies (Hibberd, 2019). A considerable proportion of worldwide apparel manufacturing occurs in economically disadvantaged countries, where the adverse societal consequences of fast fashion trends are most evident. These problems become more severe in the fast fashion industry's linear production model. The chemicals used during the production of textiles and fibers pose significant risks to workers and locals near cultivation and manufacturing facilities.

The fashion industry has caused significant harm to the environment through the cultivation of cotton that is fertilized and poisoned with dangerous chemicals and has adverse effects on the health of farmers (Angelova, 2019) and through exposure to carcinogenic substances. In addition, the untreated wastewater released into water

streams from textile mills affects the primary water sources. This pollution has adverse impacts on the health of the communities living in the neighboring regions (Bailey et al., 2022). Moreover, expanding arable land for cotton cultivation causes food insecurity issues at the household and global levels, adversely affecting the lives of people in the area (Gupta, 2021).

Along with the mentioned environmental impacts, the social and economic dimensions of the fashion industry underline its role in the deteriorating global crisis associated with a set of problems. The linear production model adopted by fast fashion points to systematic problems in the industry and highlights the need for more circular practices focusing on resource efficiency and waste reduction to redefine the norms of fashion production and consumption, prioritizing the well-being of workers and local communities affected. Considering the current practices in the fashion industry, it is clear that there is a need for a circular fashion system for well-being that goes beyond sustainability and acts in a collaborative dialogue with the ecosystem of which we are a part. Although the current models are promising, it is evident that the problem needs to be addressed more deeply. Despite current efforts and targets, it is estimated that the fashion industry will fail to achieve the 1.5°C goal by 50 percent and will need to invest an additional $20-30 billion per year to turn the textile value chain into a more sustainable one (Fashion for Good and BCG, 2020). For the fashion industry to meet the required climate targets, a 75-95% reduction in resource use from current levels is required. (Sharpe et al., 2022).

However, current production models continue to rely on high-volume production and sales as demanded by fast fashion (Braungart et al. 2007). Currently, the fast fashion industry heavily relies on extracting significant resources from the environment to make garments. However, these garments are only utilized for a short period, leading to around 73% of them being disposed of in landfills, and only Europeans use about 26 kilos of textile products every year and throw away about 11 kilos of them (Ellen MacArthur Foundation, 2017; ETC/CE Report, 2023/5).

Despite all these consequences, ‘sustainability’ is now used as a marketing strategy by many producers (Horne, 2009). As mentioned in European Commission, 2022, a study found that 53.3 % of the environmental claims made across the EU were

vague, misleading, or unfounded (European Commission, 2022). Furthermore, a fashion-specific report reveals that 60% of sustainability claims by European fashion companies are unsubstantiated and misleading (Changing Markets Foundation, 2021).

Furthermore, the fashion industry's interference with planetary boundaries does not affect everyone equally, but disadvantaged populations are the most affected, even if they have contributed the least to these boundaries (Baltruks et al., 2022). This is partly because not everyone will be similarly affected by the consequences of environmental pollution. It is essential to recognize that high-income countries are in a better position to cope with these effects because of the means and resources available to them. Therefore, they are developing slower, particularly in terms of environmental degradation. Comparatively, low- and middle-income countries are likely to face more problems in addressing these issues due to constraints in financial and technical resources, thus increasing their vulnerability to the adverse effects of environmental degradation.

When progress is referred to as the increase in the achievement of well-being in local and global contexts, and since well-being refers to the overall quality of people's lives and needs such as elements of life such as shelter, food, water, health, education, justice, freedom, and security, as well as a healthy natural world capable of sustaining ecosystem services (Hardt, J.N, 2021) must be met, it is clear that the fashion industry negatively affects physical and social well-being.

This raises the following question: Given the significant environmental and ethical issues of the fashion industry, would the physical well-being and functional benefits provided by garments mitigate the extent of their harmful effects?
The following discussion will focus on human physical and emotional well-being as a component of planetary boundaries, exploring its links to the body and clothing and its implications for fashion.

2.2. Well-being In Relation to Body and Clothing

The notions of health and well-being are often used, but the World Health Organization has a more specific definition of health. As defined by WHO in 1946,

health is a state of complete physical, mental, and social fitness and not just the absence of disease. However, this definition, which has not been changed for a long time, is weak and does not meet the present-day requirements. Now, a new definition of well-being is the level of resilience and personal control. This redefinition changes the paradigm from a state of disease non-presence to one that highlights the value of personal and community resources for sustaining health (Huber, 2011). Indeed, while the concept of health corresponds to a more medical definition, physical well-being, the effects of which are aimed to be determined in Huber's study, tends to have a more healing aspect and refers to an experience simultaneously.

The concept of well-being in relation to planetary boundaries is closely associated with human well-being and encompasses a broad range of views. While well-being has been extensively discussed in the literature regarding its psychological, emotional, and social dimensions, the relationship between fashion, clothing, and physical well-being will be discussed in the scope of this study. Nevertheless, to understand well-being better and to realize that it goes beyond mere health, the history of the definition of well-being, in general, needs to be addressed.

Eudaimonic well-being, which encompasses Aristotle's concept of eudaimonia, is among the first methods used to define well-being. Eudaimonia relates to realizing one's daimon, or essential essence, as opposed to an outcome or final situation (Moran, 2018).

Historically, well-being studies started with psychological well-being. Although it is generally identified with happiness, Bradburn (1969) suggested that well-being is more inclusive than happiness and includes both positive and negative emotions. According to Kim-Prieto et al. (2005), although positive emotions are essential indicators of subjective well-being, an individual's cognitive evaluation of his/her life is equally important. This relates to an alternative interpretation of hedonic well-being, focusing primarily on human emotions (Deci and Ryan, 2008).

In contrast to the hedonistic perspective, which centers on an individualistic approach to well-being, eudaimonia emphasizes thriving within a social setting. Therefore, well-being extends beyond mere pleasure and enjoyment to include the

soul's happiness and fulfillment. As a crucial component of positive psychology and psychotherapy, well-being is acknowledged as a higher state that denotes wealth and plenty and personal growth and development. Although the importance of living and being well is unquestionably recognized today, there is still no universally accepted consensus on well-being. (Wise, 2021).

Considering the relevance of well-being to fashion and clothing, it is seen that clothing goes beyond the need for protection and becomes a powerful tool of self-expression with a symbolic meaning. At this point, clothing is vital in enabling individuals to present themselves how they want to reflect themselves (Masuch and Hefferon, 2018). For example, 'enclothed cognition' explains how the clothes one wears can affect cognitive processes and self-efficacy perceptions (Adam and Galinsky, 2012). Emphasizes the role that clothing plays in how others perceive individuals and how they perceive themselves and their abilities. It can affect individuals' well-being by improving their mental state, performance, and social interactions. The social consideration of the relationship between clothing and well-being can mediate social interactions concerning psychological and emotional well-being. It can affect the acceptance and inclusion of the person in the social environment. (Kaiser, 1997). Apart from these, the preference for less environmental-impact garments reflects an understanding of social well-being (Joy et al., 2012).

On the other hand, clothes can directly enhance hedonic well-being through the sensory domain. In hedonic well-being, not only the sensory touch, such as wearing luxurious fabrics but also the appearance of the outfit according to design sense and even the smell of the washed clothes can also be included (Smith and Yates, 2018). In this regard, starting from the adoption of organic fibers in industry, fabrics such as vegan silk or lyocell, which have a low environmental impact and are comfortable for the user, can be associated with both social and environmental well-being in terms of their environmental impact and personal well-being, even if from a hedonic point of view, as they make the user feel good.

The concept of well-being has also passed through a dynamic of change and development from its definition confined to a medical model, namely the state in

which an individual is unaffected by any disease. However, it has been generalized to several other dynamic concepts that are closer to and deal with human beings more holistically. The concepts of resilience, the self, and eudaimonia demonstrate the need to acknowledge well-being's multifaceted nature, encompassing its mental, social, and emotional dimensions. However, although this perspective also shows the extent to which expressive and sensory experiences contribute to our well-being, and even well-being and clothing are associated with many social and psychological factors, these approaches have been further analyzed in design.

2.2.1. Well-being in the Design Context

After analyzing the definition of well-being from different perspectives and discussing the relationship between physical well-being in the body and clothing, it is necessary to comprehend what kind of perception it has in the design literature in general to better interpret its relationship with fashion design.

The concept of well-being in design is not just a theoretical construct, but a practical tool for innovation and creativity. It is based on the recognition that our environment, artifacts, and interfaces significantly impact our daily encounters, affecting our emotional state, physical well-being, and overall satisfaction with existence (Van de Poel, 2012). Emotional design, as defined by Norman (2005), involves creating products that evoke positive emotional responses in users through physical, functional and cognitive aspects. The power of this method is enhanced by Jordan's (2000) idea of pleasure design, which divides pleasure into physiological pleasure, psycho-pleasure, socio-pleasure and ideo-pleasure. This idea suggests that products can be deliberately constructed to provoke various pleasures by combining certain design elements, opening a world of creative possibilities.

These design approaches are generally product design orientated, and the relationship with well-being is mainly hedonically focused. A more inclusive body of approaches in the literature, including environmental design, architectural design, product design, and fashion design, is presented in the table below:

Table 1. Well-being in Different Design Approaches

Design Approach	**Origin**	**Definition**
Biophilic Design	Kellert et al. (2008)	It focuses on enhancing well-being by incorporating natural elements into buildings and environements that directly affect health, stress reduction and cognitive function.
Inclusive Design	Clarkson et al. (2003)	The design of products, clothing, environments and buildings that can be accessed and used by many people regardless of age, disability and other factors.
Therapeutic Design	Ulrich (1984)	Design for healing is often used in healthcare environments such as hospitals and wellness centres to reduce stress and improve well-being.
Emotional Design	Norman (2005); Desmet and Hekkert (2007)	It refers to the development of products that increase emotions, aiming to maximise user satisfaction and connection with the product.
Sustainable Design	Papanek (1972)	Reducing the environmental impact of products throughout their life cycle, from production to disposal.
Resilient Design	Vale and Campanella (2005)	Reducing negative human-generated or natural impacts through more resilient, and adaptive practices.

Although most of these design approaches have a response in fashion design, biophilic design, emotional design, and sustainable design include research within the framework of the concept of well-being.

These design approaches are generally product design orientated, and the relationship with well-being is mainly hedonically focused. A more inclusive body of approaches in the literature, including environmental design, architectural design, product design, and fashion design, is presented in the table below: Although most of these design approaches have a response in fashion design, biophilic design, emotional design, and sustainable design are the ones that include research within the framework of the concept of well-being. The biophilic design strategy is a concept based on Fromm's book Anatomy of Human Destructiveness (1973), which states that indoor natural elements can improve every aspect of a person's well-being. It refers to the use of sand, water, light, and other natural components in areas where people spend most of their time, including homes and offices, with the chief objectives being to mitigate stress and enhance the cognitive abilities and quality of life of the users (Aabouelela, 2023). Biophilic design encompasses a variety of strategies for connecting people and nature. It can be direct, including natural light, plants, and water, or through materials, colors, and patterns that mimic natural forms. '14 Models of Biophilic Design' framework provides a comprehensive guide to integrating biophilic elements to enhance well-being by expressing the effects of the environment on human biology and discusses the extent to which biophilic design in schools, workplaces, and healthcare facilities can lead to improvements in cognitive performance, psychological and physiological health (Sayed et al., 2021). The connections have been identified in prior studies exploring the correlations between biophilic features and occupant health and productivity, particularly that natural image and warm-colored areas are linked with social well-being. In contrast, natural illumination impacts psychological well-being (Alipour and Khoramian, 2023).

In the context of fashion, biophilic design endeavors to incorporate natural features to develop significant relations between people and nature, as in architecture and the environment. The emphasis on using natural textiles can increase users' connection with nature, or textiles that stimulate the senses, such as scents infused with various herbs or floral essences, encourage a deeper connection with nature.

At what stage is biophilic design, which refers to design that supports well-being by engaging with nature and bio-design, different, and why is this research focus on bio-design rather than biophilic design?

Bio-design, as a form of applying living organisms and biological processes, either directly or indirectly, into the design, aims to produce more circular systems that decrease environmental effects and increase the overall efficiency of resource utilization. It often involves technological advancements and teamwork with other scientific fields (Stefanova, 2021). An example is the application of algae for energy purposes in building systems (Deniz and Keskin-Gündoğdu, 2018). Biophilic design implies designing buildings, human-nature connections, and visual and tactile interpretations of nature. It intends to create a natural experience by replicating nature's look and feel through the materials and form or nature-based but not necessarily biological. It does not need technological enforcement (Encyclopedia of Sustainability Science and Technology Series, 2020). Unlike functionality-oriented biodesign, it mainly focuses on aesthetics. Since the field of bio-design is also developing rapidly with technological innovations, it has the potential to provide more precise, more realistic solutions in terms of contributing to the well-being of people when its principles advocate circularity and are used with a focus on functionality.

Emotional design is another design approach that should be mentioned when it comes to well-being as it relates to psychology. Emotional design is the design of products that elicit specific emotional responses, which can, in turn, be used to improve the user's satisfaction level. This entails psychological activities, human-computer interfaces, and aesthetics, which provide valuable and usable products that meet human satisfaction (Yusa et al., 2023). Various papers demonstrate that emotion affects an individual's choice and action; moreover, emotions were established to arise depending on the person's assessment concerning events and objects in compliance with Scherer's theory of emotion evaluation (2005). Thus, emotional design operates in the same line of ideas by using objects that apply positive experiences and positive affect. In the case of emotional design, aesthetic appeal is seen to have filled the gap of perceived usability, where it has been inferred

that users are more likely to perceive beautiful products as being more usable to them (Tractinsky et al., 2000). Norman (2005) identified three levels of emotional design. It is important to understand that engaging with a product involves, at the very least, visceral, behavioral, and reflective aspects; these are the aspects that define and determine user engagement. According to Desmet and Hekkert (2007), products provoke emotional responses that can guide user preferences and behavior. They classify these emotions into three dimensions: esthetic erotic functionality, and the sign. In emotional design, two significant methodologies are user-centered design and empathic design. Thus, for instance, in user-centered design, objects are created to satisfy users' needs, which are either emotional or functional (Sanders, 2002). Empathic design explains ways of getting information about consumers to help predict feelings that can be useful to the design process in understanding the consumers (Smeenk et al., 2016). Chapman (2005) proposed the concept of 'emotional durability,' mirroring that emotional design's relationship to value is not restricted to the product's design but also the product's longevity and its effects on usage, waste, and the environment.

Emotional design in fashion design focuses on enhancing the emotional connection between consumers and fashion products. It is argued that emotional responses influence decisions and are central to consumer behavior. It is stated that various sensory stimuli in fashion design, such as fabric texture, colors of garments, smells in the store, music, and even store layout and ambiance, play an essential role in shaping consumer emotions and behavior. All these sensory experiences help the consumer decide to purchase the product and build brand loyalty (Kodžoman et al., 2023). While emotional design in fashion aims to elicit specific emotions and create a sense of well-being for the user, it is more profound in the marketing aspect. To establish such a link through design, analyzing one more idea – emotional durability in fashion is more appropriate. Based on Chapman's (2008) 6-point model (narrative, detachment, surface, attachment, fiction/enchantment), attachment can also be created through a narrative that connects the wearer to the maker. Examples include pieces produced using traditional craft techniques in collaboration with local artisans that construct a narrative linking the wearer to the maker (Gwilt, 2011; Connor-Crabb, 2017). In their research, Niinimäki and Hassi (2011) have underlined the need for strategies with business models and production methods to form enduring bonds

with products. In the context of garments, Hirscher and Niinimäki (2013) showed the implication of combining in fashion where semi-finished garments lead to a higher level of engagement by the user. Although a detailed study is needed to collect information on consumer attachment, the preliminary findings suggest that the respondents are more likely to replace their current garment than add to their wardrobe after participation in the concept and the materialization of the garment. It also increased their value and preference for the co-created products. Further, Fletcher (2012) examines the effectiveness of durability at both material and product levels and extends her discourse to include emotionally durable design. However, she argues that durability does not necessarily lead to lessening consumption.

Emotional attachment to a garment does not necessarily imply that it will be worn frequently or over a long period, as material factors such as fit, fabric quality, and functionality can influence its use. Social factors also determine whether the owner has the skills or desire to repair, alter, repurpose, or upcycle the garment (Neto and Ferreira, 2020). Approaches such as emotional design, emotional attachment in design, transferred to fashion design, do not provide concrete and comprehensive research, although factors such as positive emotions, memories, and wearing experience can contribute to well-being by positively influencing a person (we feel good in our favorite clothes) (Kodžoman et al., 2023).

Among design approaches, sustainable design, arguably the most popular today, promotes environmental, psychological and social well-being. Papanek (1985) was among those who promoted design to emphasize the responsibility of designers towards society and nature and to urge designers to put ecological and social sustainability at the top of their agenda. Fuad-Luke, in his book ‘The Eco Design Handbook’ (2002), presents a comprehensive study of eco-design methods that reduce the impact of a product over its lifetime. He proposes design strategies that involve user participation, a kind of co-design that puts design power in the hands of the consumer. This structuring of design principles aligns with Papanek’s call for designs that fulfill needs without harming the environment. The social dimension of sustainable design enhances the quality of life for all living beings, fair labor practices, and contribution to social development. Manzini and Vezzoli (2003) argue

that sustainable design guarantees social equity and community participation and is central to achieving long-term sustainability goals.

From an ethical perspective, sustainable design challenges traditional production and consumption patterns. Niinimäki (2017) criticizes the disposable nature of modern consumer goods and proposes sustainable design as a path toward longer lasting and more meaningful products. This perspective is important for developing new consumer behaviors and business models prioritizing durability and repairability over disposability. In fact, it advocates for reducing the effects of environmental degradation with an emphasis on reduced waste consumption.

While the fashion industry contributes the most to environmental degradation, it is also one of the most adopting sustainable design practices. These practices include the use of recycled, biodegradable, or sustainably sourced materials. Fletcher (2008) provided a comprehensive view of the environmental challenges in fashion and suggested alternatives, particularly involving adjustments in consumer behavior. Apart from that, using environmentally friendly materials is very important in reducing the ecological footprint of fashion products. These materials include organic cotton, which is grown without harmful pesticides and chemicals and significantly reduces pollution and water use compared to conventional cotton Esteve-(Turrillas and de la Guardia, 2017). Hemp, for instance, is very sustainable since it uses water very efficiently and grows on poor soils (Gill et al., 2023). Another principal sustainable change in material treatment is using natural dyes rather than chemical ones. Natural dyes are derived primarily from plants, minerals, and even some types of bacteria, significantly reducing the toxic output of synthetic dyes (Yusuf et al., 2017). Moreover, natural finishes such as enzyme wash replace chemical finishes used to produce soft fabrics (Billah, 2019). The most valid reason why consumers generally prefer sustainable textiles is that they are usually more breathable, hypoallergenic, and free from irritants commonly found in conventionally produced textiles, offering consumers more comfort and fewer health risks (Islam et al., 2022)

Among the design approaches analysed in this part, sustainable design is the most practical approach to ensuring environmental and human well-being. However, this

discourse, which is insufficient at some points, should be extended to the circular design approach. Both will be discussed in detail under the title ‘Impact of Sustainable Textiles in Fashion on Enhancing Well-being’.

2.2.2. Historical Evolution of Well-being in Relation to Fashion Design

The historical evolution demonstrates that the pursuit of well-being, now a contemporary trend, has roots that extend far into earlier times. Although the idea of well-being in fashion design has only recently emerged in the literature, it has become a trend from time to time, identified with health, and changed the clothing choices of users. Women have adapted their relationships with their bodies and clothing to changing physical needs, thus constantly seeking greater freedom of movement and comfort throughout history. Thus, the present search for a trend for well-being is not new; it dates to much earlier. The historical chain of events indicates that the taste of wearing clothes has always been affected by historically influential and world-affecting events. These events are political or economic, including changing lifestyles, challenges to traditional gender norms, art movements, and technological innovations.

At the beginning of the 20th century, art movements such as the Vienna Secession underlined the connection between artistic freedom and physical well-being. They advocated a holistic approach to art and life. While in interwar Vienna, women's artistic contributions were marginalized as merely feminized crafts as opposed to works of fine art, the women of the Vienna Women's Academy provocatively subverted gendered hierarchies between art and craft (Schweiger, 2021). The Vienne Secession played an essential role in integrating well-being into aesthetic discourse, and its emphasis on natural forms and rejection of the rigid constraints of previous artistic traditions paralleled the emerging spa culture in Vienna, where the integration of natural landscapes and health-oriented architecture encouraged a holistic approach to well-being (Silverman, 1989). Spa culture, epitomized by venues such as the Wien Heilquellen, became centers of physical regeneration and social gathering, reflecting the Secession's ideals of beauty and health (Houze, 2001). The Secessionist movement heralded a significant reform in women's fashion, with profound implications for women's health. The shift to looser clothing, which allowed more movement and was less restrictive than traditional corseted clothing, was a key

aspect of this reform. Unlike the tight corsets and structured corsets of traditional Victorian fashion, reform dresses often featured flowing lines that did not constrict the body, thereby promoting better circulation and respiratory health. The transition from heavy silks and brocades to natural fibers such as wool, cotton, and linen, which were more breathable and comfortable, further enhanced the health benefits of these new fashion choices. This blend of health, comfort, and style came to symbolize modernity and freedom for women, underscoring the positive impact of fashion on women's well-being. Parallel to reform dress, health corsets, which aim to support the body rather than constrict it, have emerged as a less restrictive alternative to traditional corsets. These changes in undergarments were part of a broader shift towards garments that respected the wearer's physical health and comfort. In the early 20th century, these ideas permeated mainstream fashion, transforming women's clothing into symbols of modernity and aesthetic expression in line with new artistic movements (Cunningham, 2003).

Alongside these liberating developments, in the early years of the 20th century, corresponding to the preparing grounds of modern fashion design, the First World War forced humanity to substantial changes in clothing, based instead on the utility and functional aspects. The clothes women wore when they started working placed new demands and consequently necessitated the adoption of more straightforward and practical clothing. (Figure 2). These functional clothes meant that physical comfort would increase and symbolized progress towards greater gender equality by providing an environment where women could feel as comfortable at work as men (Ribeiro, 1986).

Figure 2. Women at work with their comfortable clothes at ship construction in Seattle, Washington, 1919 (Source: history.com, 2021)

During the 1920s, fashion became a signifier of modernity, freedom, and deviation from the norms traditionally accepted by society, causing styles such as the flapper style, a specific style with dresses reaching only to the knees, blunt hair, and a more androgynous silhouette (Figure 3) (Park, 2014). This new style is a sign of psychological and social well-being, a reflection of the increasing independence and freedom of the woman.

Figure 3. 1920's flapper dresses (Source: scotneycastlent.wordpress.com, 2015)

On the other hand, by the 1930s, athleticwear reached its peak popularity when the importance of leisure time began to be recognized, and physical activities were finally fully entering the popular consciousness (Osborne and Skillen, 2020). Women's sportswear was part of the more significant cultural movement towards health and well-being concerns, with shorter skirts for tennis and the beginning of women swimming (Figure 4).

Figure 4. Verna Lee Fisher sporting her newly swimsuit at Palm Beach, 1933 (Source: time.com, 2016)

The Second World War played a critical role in changing the style of women's clothes out of material constraints and practical needs. The utilitarian style, practical clothing made from simple, functional cuts using durable materials, has become widespread (Arnold, 2001). Women wore trousers, overalls, and uniform-like dresses, all practical with flair, to occupations in wartime factories and other work (Figure 5).

Figure 5. A woman checks out the Utility suit collection in a London department store, 1942 (Source: babel.ua, 2022)

Besides, it also pointed to the birth of post-war fashion trends regarding clothing, as this practice was quite simple and functional. On the other hand, the post-war economic boom of the 1950s created more leisure time and popularized sports (Figure 6). Technological innovations in textiles, such as the development of synthetic fibers like nylon and polyester in the 1950s, significantly improved the functionality and comfort of clothing. This revolution in textile technology was a game-changer for sportswear, making it more durable and suitable for physical activity (Tsoumas, 2024).

Figure 6. 1950’s workout in a floral playsuit (Source: vintagedancer.com, 2020)

The 1960s—1970s can be credited with one of the most spirited epochs in fashion and clothing, inspired by postmodernism. This period was characterized by rejecting the conservative norms of previous decades and adopting intense colors, unusual fabrics, and innovative designs (Blancoa and Reilly, 2021). Mary Quant's introduction of the miniskirt during this period symbolized youth rebellion and the ongoing struggle for women's emancipation, embodying the counterculture that was the era's spirit (Steele, 2000). The 1970s witnessed a significant shift in athletic wear and sportswear with the fitness boom and the rise of running, aerobics and other physical activities. Brands such as Adidas and Nike introduced innovative designs and materials that improved performance and comfort (Smith, 2007). The popularisation of fitness culture in the 1970s had a profound impact on well-being by promoting a more active lifestyle and improving physical health (Figure 7). The fitness movement not only challenged traditional notions of female fragility but also promoted strength, endurance, and empowerment. Women began to embrace athletics and physical fitness as part of their identity, which contributed to both their physical and psychological well-being (Dworkin and Wachs, 2009).

Figure 7. 1970s leotards (Source: vintagedancer.com)

The 1980s were characterized by excess and extravagance in fashion, reflecting the economic boom and consumerism of the period. The fitness craze during this period led to the widespread adoption of athletic wear as everyday fashion. Leggings, swimsuits, and tracksuits became famous in gyms and on everyday occasions (Figure 8).

Figure 8. A fitness studio in New York, 1984 (Source: Sue Ann Miller for The New York Times)

It has also blurred the lines between work, leisure, and exercise, making it easier for women to incorporate physical activity into their daily routines. This trend has promoted fitness and well-being, increasingly recognized as essential components of a healthy lifestyle. This represented a paradigm shift in the way women viewed their physicality. Anthropologist O'Connor (2011) stated that "Lycra became the second skin of a new life in which self-confidence was rooted in women and their bodies, not in rules, not in dress codes, not in wearing clothes 'appropriate' to age or social status, and especially not in wearing a corset."

The minimalist trend of the 90s favored simplicity and function over excess. This minimalist aesthetic contrasted with the opulent styles of the previous decade. This allowed women to focus on comfort and personal expression rather than adhering to elaborate fashion norms (Svendsen, 2006). Since the early 1990s, Princess Diana has been a trailblazer in demonstrating how elegance and trend can be harmonized in contemporary clothing. Through her choice to wear practical sportswear pieces, her influence on sportswear has underscored the significance of aesthetics and comfort in women's fashion (Beaton, 2014). Her iconic sportswear fashion choices, featuring sweatshirts, cycling shorts, and trainers, set a trend during her time that continues to be popular today (Figure 9).

Brands like Nike, Adidas, and Reebok began catering to women by introducing practical sportswear lines. Sports bras, leggings, and clothes that absorb sweat have become more popular, providing women better comfort and support during physical activities. These garments are designed to enhance athletic performance while being stylish enough to be worn outside the gym. With yoga becoming a trend, posture, flexibility, and correct use of the body have come to the forefront among women, and yoga clothes have become popular, giving birth to the mindfulness trend and emphasizing inner peace (Ding and Stamatakis, 2014)

Since the 2000s, the fashion industry has increasingly embraced the concept of well-being, driven by a shift in consumer expectations towards health, sustainability, and ethical production. The rise of athleisure in the early 2000s serves as a prime example of this trend, where comfort and functionality are elevated as crucial considerations in everyday wear. From the mid-2000s onwards, the growing

environmental consciousness has spurred the fashion industry to pioneer sustainable practices and new materials (Gwilt, 2020).

Figure 9. Diana leaving the gym (Source: Brendan Beirne for Shutterstock, vogue.co.uk)

This was followed in the late 2010s by technological innovations that improved user interaction and health monitoring with the emergence of wearable technology and intelligent fabrics (Clarke, 2023). The smartwatches are one example of the health monitoring trend. The COVID-19 pandemic in the 2020s has created a vast market, focusing on innovative textiles and casual yet professional homeware, emphasizing the importance of health, safety, and comfort (Skivko, 2020). With concepts such as inclusivity and body positivity on the rise in fashion, the new shapewear trend where women declare their freedom through their curves, which includes shapewear designed to increase comfort and confidence for different body types (Hampton and Bryan, 2024) (Figure 10). Thus, women have launched an unprecedented era of clothing comfort.

The evolution of fashion design in relation to affluence is a testament to the dynamic relationship between societal changes and fashion's ability to adapt to women's evolving needs and values. This narrative continued into the late 20th and early 21st centuries, with a heightened focus on health, inclusivity, and sustainability. These shifts were heavily influenced by technological advancements and a growing global consciousness, further highlighting the pivotal role of fashion in women's daily lives. The COVID-19 pandemic brought comfort, functionality, and well-being to the forefront of fashion design, underscoring its adaptability and responsiveness to societal needs.

Figure 10. Shapewear brand SKIMS shapewear (Source: cosmopolitan.com, 2023)

The next discussion, 'The Impact of Sustainable Textiles in Fashion on Enhancing Well-being,' explores the link between sustainability principles and well-being. It considers the role of circularity and how it relates to developments in bio-based textiles to better understand environmental impacts.

2.3. Impact of Sustainable Textiles in Fashion on Enhancing Well-being

The fashion industry is marked by swift shifts in trends and a continuous output of new clothing, significantly influencing the economy and the global environment (Brewer, 2019). Our society's prevalent throwaway culture is increasingly manifesting in the fashion sector, leading to the rise of 'fast fashion' – a tendency towards disposable, low-cost clothing. However, this fast fashion model has brought

about adverse environmental and societal effects that warrant careful examination. Global fiber production has almost doubled in the last 20 years, reaching 58 million tonnes in 2000 and is expected to reach 147 million tonnes in 2030 (Textile Exchange, 2023). Synthetic fibers like polyester, acrylic, nylon, and polyamide constituted 63% of these fibers, with cotton comprising 26% and the remaining 11% comprising various natural and synthetic fibers, including viscose and wool (Ellen MacArthur Foundation, 2017).

The fashion industry's material consumption goes beyond fiber usage, involving the substantial use of chemicals for dyeing and finishing textiles, along with cardboard and plastic for the logistics of textile storage and transport (Šajn, 2019). This illustrates the numerous steps in textile production, resulting in substantial energy consumption, including the energy used for sewing machines and other manufacturing equipment (Sajn, 2019).

The linear practices of the fashion industry are causing the depletion of vital natural resources, pollution of aquatic ecosystems, and detrimental impacts on the physical and social well-being of workers in the industry. The perception of clothing as disposable items overlooks the intricate and extensive supply chains in the textile and fashion industries, leading to the overuse of resources (Jacometti, 2019). While these issues primarily affect the countries where textiles and garments are manufactured, their effects are felt globally. This has spurred the development of new materials and the reassessment of existing ones, as there is a growing demand for more sustainable and ethically responsible alternatives in the fashion industry (McNeill and Venter, 2019).

When we consider the broader concept of sustainability, it becomes evident that addressing these challenges requires a comprehensive approach that spans the entire life cycle of garments. This approach involves enhancing the social environment and tackling the cradle-to-grave environmental aspects of the industry, from raw materials to product disposal. Therefore, this comprehensive approach to implementing the core idea of sustainable fashion shifts the focus from the environment to a perspective where it is complemented by equally important social

aspects, making it the optimal model of ethical fashion for the well-being of humans and the planet.

2.3.1. Sustainability and Textile Innovation

Sustainability practices ensure that all stages of a product's life cycle, from the materials used to the manufacturing processes, are safe and beneficial for people and the environment. This approach involves selecting materials that can be reintegrated into natural or industrial ecosystems and contribute to social well-being at all stages of the product's life.

Sustainability concerns in fashion include social aspects such as labor treatment and workers' well-being within the production process. Concurring with Ditlev-Simonsen (2022), the Rana Plaza tragedy in 2013 brought attention to fatal building collapses that killed over a thousand garment workers and pointed to the human dimensions of this industry. Ensuring social sustainability includes implementing stricter labor regulations, ensuring fair wages, and improving working conditions. Initiatives such as the Fashion Revolution and certifications such as Fair Trade are critical in promoting transparency and accountability (Brun et al., 2020).

Promoting human well-being within Earth's biocapacity requires an integrative strategy that addresses post-growth and alternative economic models. This strategy should not only promote equality and environmental conservation but also respect and empower indigenous people. Their role in the process of the planet's transformation to well-being is crucial. Their ancestral knowledge is immensely beneficial in fostering sustainable resource management and living in harmony with the environment. A transition to a circular economy must be both fair and equitable. It should cater to the needs of at-risk communities, ensure just allocation of resources and opportunities, and enable marginalized groups to have a voice in decision-making (Ensor and Hoddy, 2021).

Reducing water and chemical use in the fashion industry is crucial for reducing environmental impact, especially in water-scarce regions where textile production exacerbates water scarcity. Approximately 2,700 liters of water are required to

produce enough cotton for a single T-shirt, underlining the significant water demand of the industry (Mellick et al., 2021). Textile processing is another activity with high water consumption rates; in dyeing operations alone, tens of thousands of liters of water are typically consumed (Samanta et al., 2019). Toxic chemicals such as nonylphenol ethoxylates and heavy metals are often emitted to waterways from textile wet processes, causing adverse effects on aquatic life and human health (Khan and Malik, 2014). In the textile industry, advancements in technology like air dyeing and digital printing can help decrease water usage by making dyeing and finishing processes, thereby reducing the need for water and chemicals (Lara et al., 2022). Industry standards set by organizations like OEKO-TEX and Bluesign establish guidelines for limiting emissions into air, water, and soil while promoting raw material utilization (Almeida, 2015).

Regenerative practices, another sustainability solution in the fashion industry, focus on restoring affected ecosystems and communities caused by fashion productions. These are practices like regenerative agro-producing naturally sourced fibers like cotton. It also enhances soil integrity and diversity, as well as no-till farming, crop rotation, and organic farming, which excludes synthetic input. These systems need to innovate for effective water management in areas such as rainwater harvesting and wastewater recycling (Larsen et al., 2016). In addition, carbon dioxide is sequestered through agricultural methods and the production of carbon-negative materials that store more carbon than is released into the atmosphere (Don et al., 2023). Moreover, it enhances ecosystem services and biodiversity by planting endemic species and creating habitats to increase biodiversity. Moreover, it is also essential to implement fair labor practices and support local economies, as discussed earlier.

Although the harmful effects of textile production are attempted to be prevented by various measures, consumer behavior and education are critical to promoting sustainability in the fashion industry, primarily by raising awareness of environmental and social impacts. Educating consumers about the environmental costs associated with garment production, such as water pollution, carbon emissions, and the social injustices prevalent in the industry, can lead to more informed and responsible consumption choices (Lubowiecki-Vikuk et al., 2021). Of the environmental and social footprint of a product, a company can adopt transparent

labeling, which is among the strategies effective consumer engagement strategies, an advertising campaign that emphasizes a company's sustainability effort, and affiliations with environmental groups or organizations (James and Montgomery, 2017). Additionally, interactive platforms and mobile applications may be used to provide educational content and valuable features that help users see the effect of their fashion choices on sustainability. Besides this type of public event, workshops are also held, facilitating direct participation between communities and sustainable practices, such as upcycling and repair (Wu et al., 2023).

Moreover, encouraging policies that support sustainable practices can lead to systemic change within this industry. Collaboratively, all these efforts enable consumers to buy products that match their values, increasing demand for sustainable goods, thus instilling culture into the fashion business and leading it towards longevity. Consumer behavior towards the care and maintenance of textiles and clothing can also negatively impact the environment. For example, Laitala et al. (2018) and Jacometti (2019) noted that care procedures such as washing and drying clothes require water, electricity, and chemicals. Furthermore, household laundry contributes to microfiber pollution in the sea, as microfibres are separated from textiles and end up in rivers. Customers can minimize these impacts by avoiding wasteful washing and limiting the degree of washing. Although most microfibres can be removed from water through advanced water treatment, significant quantities still enter water bodies through different effluents and are consumed by marine organisms, and as a result, plastic fibers move deeper into the food chain (Gaylarde et al., 2021).

In a system where the fashion industry is constantly in need of new raw materials, sustainable practices are sometimes insufficient alone in this struggle and should be supported by circular strategies. Benchmarking environmental impacts is a complex endeavor fraught with numerous challenges. These include the non-standardized nature of fiber production practices, which are influenced by changing production techniques, technological advances, and regional environmental regulatory differences. It is clear that external factors, such as climate change, water scarcity, and the availability of resources also play an important role in determining the environmental impacts of any given situation. However, this task is further

complicated by the difficulty of obtaining precise and all-encompassing data, as well as the inconsistencies that inevitably arise when comparing different impact assessment studies, due to various presuppositions regarding system boundaries. It can be argued that while textile products may be perceived as sustainable and chosen for their emotional appeal, they may fail to significantly improve well-being unless their production processes are fully transparent, ensuring the credibility of their sustainability claims.

2.3.2. Circularity in Textile Industry

Circularity in fashion refers to a sustainable system that optimizes the usefulness and value of goods throughout the different life cycles of design, production, and management, as opposed to the traditional linear 'take-make-dispose' model to reduce waste and environmental impact (Rathinamoorthy, 2019). An essential component of this model is the proposed by Braungart and McDonough (2002) cradle-to-cradle approach, which emphasizes that materials used in products should be fully reusable or biodegradable so that they can either safely return to the earth or enter circulation without quality degradation. The cradle-to-cradle model classifies all materials (metal, fiber, dyestuff, etc.) in the industrial and commercial processes under technical and biological 'nutrients' (Figure 11). This distinction particularly highlights the literal meaning of 'consumption.' While in the current linear industrial system scope, 'consume' is synonymous with 'use' and 'generate waste,' in design-based cradle-to-cradle consumption means 'destruction' and 'rot.'' The cradle-to-cradle design principle is the foundation of 'waste = food' underlines whether resources are wasted in nature's continuous cycles and that they are repeatedly used to create new resources.

"Everything is a resource for something else. In nature, the 'waste' of one system becomes food for another. Everything can be designed to be disassembled and returned safely to the soil as biological food or reused as high-quality materials for new products as technical food without contamination." McDonough and Braungart (2002).

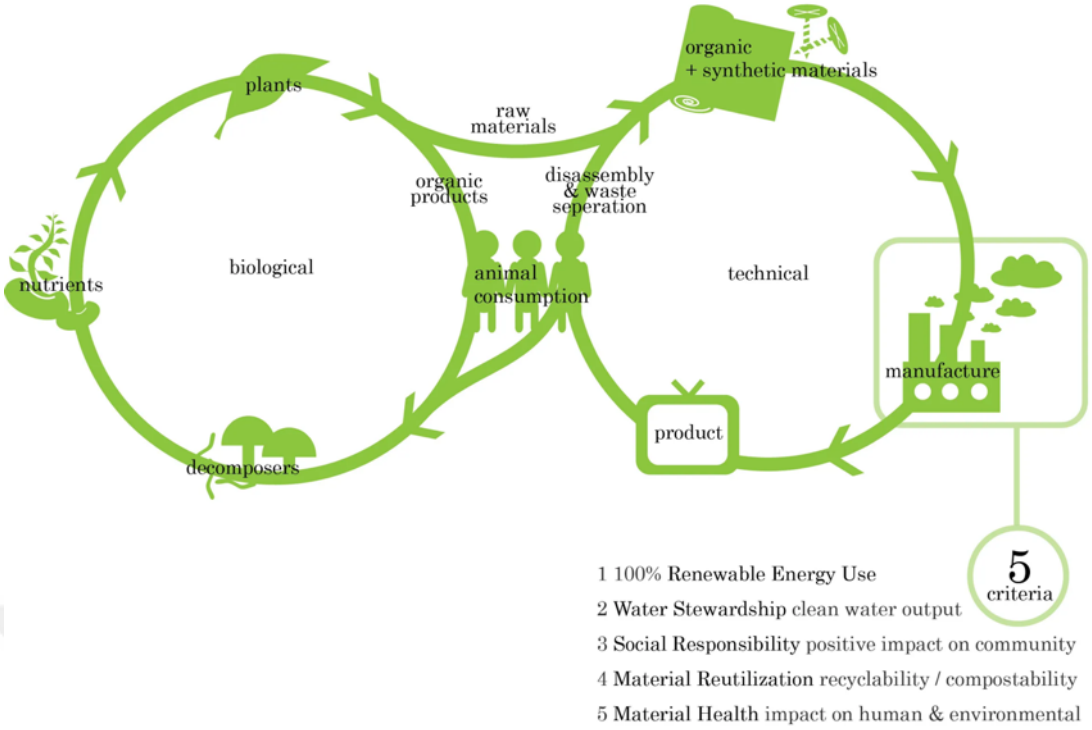

Figure 11. An illustration of the distinction between our material flows (Source: Kylie Calian, medium.org, 2016)

In nature, the principle that 'the waste of one system feeds the other' is extremely important for the textile industry, especially when integrated with bio-design principles. This concept underlines the transformative approach where waste materials from one process become valuable resources for another process. In textile production, every fiber, dye, and by-product can be strategically designed to return to the ecosystem unharmed or be transformed into new, high-quality materials (Podara et al., 2024). Materials should be selected based on their ability to biodegrade cleanly into the environment as biological nutrients or quickly recaptured and recycled into new products as technical nutrients. For example, biodegradable textiles, such as those developed from bio-based fabrics, can decompose naturally and contribute positively to the soil when no longer usable. This eliminates waste and feeds the agricultural base needed to grow more raw materials, helping create a truly sustainable production cycle. (Nofal, 2023).

According to Korhonen et al. (2018), economic and natural systems that are 100% dependent on renewable energy are integrated into a single system in the circular economy concept. However, only 25 % of the planet's energy is renewable.

Moreover, from this point of view, this is almost impossible due to organizational and cultural limitations. Based on these challenges, the authors set two objectives: to establish a definition of the circular economy in line with a sustainable development perspective by defining the three dimensions of sustainable development and planetary boundaries and to identify six barriers to be overcome for the global contribution of the circular economy. Defining the circular economy from the perspective of sustainable development in domestic and international markets, the authors explained that the circular economy is a collaborative economy built with circular materials and a social production system that flows through energy resources and energy production flows that maximize service through social-nature flow.

Economic growth is the primary goal of today's industrial and capitalist system, which risks the planet's well-being. Thus, an essential step in the application of circularity principles in design represents the transformation where closed-loop systems have emerged due to the theoretical impossibility of producing an unlimited number of products from the same resources. (Kara et al., 2022).

'Design for circularity' is not a new concept but an evolution of earlier models like the 10R framework. This new approach offers a more detailed and strategic way of thinking about circularity. The 10R framework, which includes principles like reduce, reuse, recycle, redesign, recover, rethink, remanufacture, repurpose, repair, and refurbish, has paved the way for this more comprehensive and strategic approach to circular design (Figure 12).

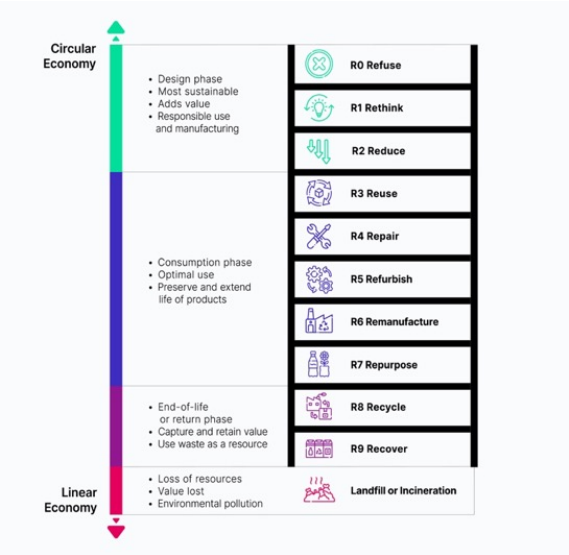

Figure 12. The different stages of R-Strategies (Source: circularise.com, 2023, adopted from et al., 2017)

The first principle, 'refuse', concerns the critical evaluation of the need to create a new fashion product. It challenges the fast fashion model by advocating the elimination of unnecessary garments, which contributes to reducing excessive waste and resource consumption in the fashion industry. (Jimenez-Fernandez, 2023). Rethinking involves designing garments with their entire life cycle in mind and ensuring they are easier to reuse, repair, or recycle. It encourages innovations in fashion design, such as modular garments that can be easily replaced or repaired, thus extending the garment's life and adapting to changing consumer needs without compromising sustainability. (Fontell and Heikkilä, 2017). Reduce aims to minimize the materials and energy used in garment production. Fashion companies can significantly reduce their environmental footprint by optimizing production processes and integrating sustainable practices such as using eco-friendly materials. (Keßler et al., 2021). Reuse focuses on extending a product's life by using it more than once. Extending the lifespan of fashion products by designing them to withstand repeated use is a vital sustainability practice. This may involve establishing systems for high-quality production or garment exchange, resale, or rental services that keep garments in circulation longer. (Palm et al., 2021). Encouraging consumers to repair damaged clothing instead of throwing it away supports sustainability by extending the life of products. Fashion brands can contribute by designing clothes that are easier to repair, offering repair services, or providing spare parts and instructions to facilitate DIY repairs (Johansson and Stubb, 2021). In the context of the

refurbishment process, previously used products are restored to a state of functional usability. This entails returning previously used garments to a usable condition with minimal changes such as cleaning or minor alterations. Refurbishment helps to preserve the value and functionality of fashion items for longer and offers a less resource-intensive alternative to producing new items (Keßler et al., 2021). Repurpose is transforming waste materials or outdated garments into new, usable garments that encourage creativity and innovation. The principle in question fosters innovation and the creation of items that can be utilized repeatedly for many purposes throughout their life cycle (Johansson and Stubb, 2021). Textile recycling is recovering textile waste (pre- and post-consumer) and reprocessing the material into new garments (Fashion for Good, 2022). Mechanical recycling involves breaking down fabrics into fibers that can be spun into new yarns and is limited by the reduced quality of the fibers after recycling. On the other hand, chemical recycling involves polymer and monomer recycling. It separates fibers into their chemical components to create new fibers, but it often involves toxic chemicals and high energy use (Ribul et al., 2021). Alternatively, emerging bio-based processes in textile recycling are categorized as biological, biochemical, and fermentation processes, each using different methods and microorganisms to break down or convert textile materials into simpler molecules (Ribul et al., 2021). Recovery, however, refers to extracting usable products or energy from waste that cannot be reused in the usual manner. This can involve decomposing organic waste to create nutrient-rich soil and harnessing the energy potential of waste products. The objective is to optimize the utilization of every stage in the life cycle of a product (Morseletto, 2020).

Material innovation, the cornerstone of this study, plays a pivotal role in the transition from linear economic models to circular economic models. In a circular economy, which underscores the need for materials that can be reused or composted, the goal is to maintain their value within the system for as long as possible (Moreno et al., 2016). Specialized technological advances in materials science, including the synthesis of biodegradable biopolymers and the emergence of advanced recycling techniques, are instrumental in supporting the types of designs that can foster circularity (Cobra et al., 2021). The integration of material innovation into circular design necessitates a paradigm shift in the way designers approach material selection and utilization. It is imperative to move beyond designing with existing materials to

designing new materials tailored for specific circular applications. This shift requires interdisciplinary collaboration between designers, scientists and industry stakeholders to develop materials that meet both functional and environmental criteria (Squatrito and Ferrara, 2023).

The fashion industry's environmental footprint, which spans from textile production to dyeing processes and logistics, underscores the pressing need for radical changes. These issues will be explored in the following section through the examination of alternative textiles such as bio-based fibers. To effectively tackle the complex challenges facing the fashion industry, a comprehensive system overhaul is essential, encompassing advances in materials, transparency in production processes and a strong focus on circular economy principles.

2.3.3. Bio-based Textiles

Fiber production for garment manufacturing is the primary source of environmental damage in the supply chain. Natural fibers like organic cotton, bamboo, hemp, jute, and ramie are widely recognized as eco-friendly alternatives in sustainable textiles. They offer a range of benefits, including reduced water and energy consumption, and lower carbon footprint, making them a sustainable choice for the environment.
The conventional bio-based textiles in the industry are categorized in the table below;

Table 2. The different types of bio-based textiles, along with their positive and negative aspects, biodiversity and circularity, biodegradability, recycling and waste management

Category	**Bio-based Textiles**	**Positive Aspects**	**Negative Aspects**	**Biodiversity /Circularity**	**Biodegradability/ Recycling/Waste Management**
Natural Cellulosic Fibers	Organic cotton, bamboo, hemp, jute, ramie	Lower greenhouse gas emissions Potential for biodegradability	High water and land usage for cotton. Hazardous chemicals in dyeing and processing pesticides in cultivation	Promotes biodiversity if managed sustainably.	High potential for biodegradability but challenges in recycling textile waste. High waste production, majority ends up in landfills.
Animal-Based Fibers	Wool, leather	Durable and can be sustainably sourced	Methane emissions from livestock. Environmental impact from leather processing	Low impact on biodiversity unless sustainably sourced.	Low biodegradability due to chemical treatments. Difficult to recycle and often ends up as waste
Man-made Cellulosic Fibers	Viscose, modal, lyocell	Made from renewable wood pulp, reducing fossil fuel reliance. Can utilize recycled cellulose.	Dependent on harmful chemicals used in production.	Can be part of a circular economy if recycled materials are used.	Generally biodegradable, but recycling processes are not widely profitable. Recycling infrastructure is insufficient

While bio-based textiles are traditionally considered sustainable in fashion, heavy industrialization means that sustainability is only sometimes guaranteed, even with natural materials. The production of these textiles can help reduce greenhouse gas emissions but also requires significant water and land resources (Zhao et al., 2021). For instance, animal-based materials such as wool and leather produce methane emissions, accounting for a significant portion of global greenhouse gases (ETC/C Report, 2023). Furthermore, cotton, a prevalent natural textile, heavily relies on water for its growth. It is estimated that textile industry activities rank as the second major polluter of the world's freshwater resources, contributing to 20% of total pollution. This is mainly due to the hazardous chemicals used in fabric dyeing and processing and pesticides used to cultivate raw materials (Mellick et al., 2021).

Hemp and flax, two natural fibers, are emerging as superior alternatives to conventional cotton. Hemp, for instance, requires only a quarter of the fertilizer needed for cotton, along with fewer seeds, less field care, and lower irrigation costs (ETC/C Report, 2023). It also outperforms cotton in terms of productivity, yielding three times more fiber per hectare. This higher yield, coupled with a 75% cost reduction due to decreased requirements for fertilizer, seeds, irrigation, and pest control, positions hemp as a more eco-friendly and economically viable substitute for cotton (ETC/C Report, 2023:5). Flax, on the other hand, demands less fertilizer than hemp but requires more pesticides (González-García et al., 2010). Compared to cotton, flax, and hemp cultivation generally require less water, resulting in a smaller environmental footprint. Land use is the primary environmental concern for Flax because other impacts are relatively minor (Fernando et al., 2015). In contrast, cotton is often grown in water-scarce subtropical regions and relies heavily on irrigation and extensive agrochemical use to maintain crop yield levels (La Rosa and Grammatikos, 2019). Although hemp and flax fibers undergo additional processing such as degumming, which refers to the separation of cellulose and non-cellulose fractions and involves significant water use, this process accounts for only about 1% of the water used for irrigation of cotton (Turenen and van der Werf, 2006). The environmental impact of these fibers during the growth phase is generally lower than cotton's. However, degumming can increase their environmental impact depending on the method and energy source used (Lyu et al., 2021).

In the past few years, synthetic cellulosic fibers such as viscose, modal, and lyocell have gained prominence as eco-friendlier options compared to synthetic textiles from fossil fuels like polyester and resource-intensive options like cotton (Felgueiras et al., 2021). These fibers are generally made by melting down wood pulp, and the environmental impact is primarily determined by the chemicals and raw materials used in this melting process. Viscose fibers from recycled cellulose, which comes from textile waste, are less environmentally damaging than those made from fresh cellulose (Felgueiras et al., 2021) The environmental efficacy of the textile fiber industry varies considerably and is influenced by various manufacturers' diverse production and sourcing practices. An alternative strategy is to manufacture synthetic fibers from biological sources to reduce dependence on fossil fuels and minimize environmental impacts. Although chemically similar to their fossil fuel-based counterparts, these bio-based synthetic fibers are made from carbon derived from renewable resources. They are often regarded as more sustainable than traditional virgin fossil-based fibers. The key to their sustainability is sourcing sustainable raw materials that avoid competition with food crops for land and minimize reliance on water and chemicals (ETC/WMGE, 2021). Evaluating the environmental sustainability of bio-sourced synthetics and broader bio-based fibers is crucial. A key issue arises with first-generation feedstocks like food or dedicated fiber crops, which can lead to increased eutrophication, ecotoxicity, and land and water use. Precisely, substituting petrochemicals with crops elevates the demand for primary inputs due to changes in feedstock and processing (Ivanović et al., 2021). However, the environmental impact can vary greatly depending on the bio-content and the choice of feedstock. For example, bio-based polyester made from sugarcane may have similar environmental effects as its petrochemical counterpart, while bio-based polyester from maize shows poorer environmental performance (Ivanović et al., 2021). In summary, when bio-based synthetic fibers are predominantly agricultural-based, it is vital to be cautious in considering them as eco-friendly options.

In the realm of sustainable textiles and their impact on the fashion industry, the issue of waste management looms large. Currently, less than 1% of clothes discarded annually by consumers are repurposed into new products (McKinsey & Company, 2022). Recycling textiles poses further challenges due to their unprofitability and the labor and energy-intensive nature of the process, leading to a significant portion of

these textiles ending up in developing nations needing proper recycling infrastructure. There is a common but false belief that bio-based materials or textiles are always biodegradable. The reality is that biodegradability is determined by the type of polymer used (Garrison et al., 2016). While fibers derived from natural or modified natural polymers can degrade, bio-based synthetic polymers cannot. Furthermore, biodegradability does not imply the possibility of uncontrolled textile disposal. Effective waste treatment is necessary to ensure the proper decomposition of textiles, regardless of whether the textiles are biodegradable or compostable (Egan and Salmon, 2021). However, biodegradable fibers may contribute to methane production under anaerobic landfill conditions, a greenhouse gas more potent than carbon dioxide. Processing chemicals and finishing agents may also affect fiber biodegradation negatively, hindering proper breakdown. Toxic metals in dyes can impede the bacterial activity required for biodegradation or harm the compost produced (Sharif, 2020). It is also possible that certain dyes could cause environmental problems if released into the environment. It is common for textiles to be processed and finished, which causes garments composed of biodegradable materials to contain chemical residues from those processes or have non-biodegradable material components such as stitching, labels, and buttons. Nevertheless, biodegradability alone is not sufficient for current textile production practices.

Apart from conventional bio-based textiles, new-generation bio-based textiles offer more opportunities than the existing ones with the developing technology. Moreover, these textiles are considered more attractive by users due to their positive environmental effects and beneficial properties for well-being. The following table presents some new-generation bio-based textiles, their sustainable properties, and their benefits.

Table 3. List of selected new generation bio-based textiles

Textile	Source	Sustainability Features	Benefits
REFIBRA™	Recycled cotton scraps and wood pulp	Recycling of cotton waste Closed-loop process Less CO2, water, energy use Multiple certifications	Skin-soft touch, Thermal regulation
Texloop™ RCOT™ Primo	Recycled and organic cotton	Up to 50% recycled cotton Less CO2, water, energy use GRS, OCS certified	100% cotton, breathable
C4 Cotton	Climate Beneficial™ cotton from California	Regenerative farming Improved soil health Traceable Supporting local economies Climate Beneficial certified	Natural fiber, made in California
Creora® Bio-Based	Spandex made with 30% bio-based materials from field corn	20% reduced carbon footprint vs regular spandex SGS Eco Product certified	High strength, resistance, optimized recovery
SeaCell™	Cellulose fiber enriched with brown seaweed	Sustainable harvesting Biodegradable	Moisture regulating, soft, skin-nourishing

The field of bio-based textiles is undergoing significant developments. The boundaries between these textiles, previously limited to natural fibers, are now being redefined by the advent of new active materials and scientific procedures.

SeaCell™, evaluated in Table 3 and forming the basis of the industry collaboration part of this study, is an innovative bioactive textile fiber that combines the beneficial properties of seaweed with the physical properties of Lyocell fibers. This fiber's composition, properties, skin benefits, and application areas will be discussed in detail in the practical implementation Chapter 4.

There is a pressing need for circular strategies to ensure a steady supply of novel raw materials. However, the comparison of environmental impacts is a complex and challenging task. The non-standardized nature of fiber production practices, influenced by varying techniques, technological advancements, and regional environmental regulation disparities, adds to the complexity. External factors like climate variations, water shortages, and resource accessibility also significantly influence environmental impacts. The difficulty of obtaining precise, comprehensive data, and the inconsistencies that arise when comparing different impact assessment studies, primarily due to the varied presuppositions regarding system boundaries, further complicate the task (Boström and Micheletti, 2016). In this context, it becomes clear that textiles, despite their sustainable claims and emotional appeal, may not significantly enhance well-being unless their production processes are transparently understood and managed.

While the fashion industry is making strides in addressing its environmental impact through the exploration of alternative textiles such as bio-based fibers, these alternatives, while potentially beneficial, also present diverse environmental challenges. Issues such as water and soil consumption, chemical processing, and wider sustainability are significant hurdles. For instance, the use of raw materials like organic cotton, hemp, and flax can mitigate some environmental issues, but they are far from a comprehensive solution when all life cycle impacts are considered. This underscores the urgent need for the development of innovative materials inspired by bio-design. This transformative strategy involves a shift from reliance on non-renewable resources to the adoption of renewable resources and a commitment to waste minimization throughout the entire product life cycle, a change that is not just desirable, but necessary for the future of sustainable fashion.

Following the analysis of the link between fashion and well-being, the next chapter of this study will critically evaluate the role of bio-design and current developments in material innovation, which is the second significant focus of this research.

CHAPTER 3: EMERGING ROLE OF BIO-DESIGN IN FASHION PRACTICE

As the fashion industry continues to evolve and adapt, new approaches are emerging that combine the worlds of biology and design. These innovative approaches, known as bio-design, have added a new dimension to fashion's ecological and social challenges, drawing inspiration from the natural world and incorporating biological principles to create innovative and circular fashion design solutions. This chapter examines the link between bio-design, fashion, and well-being. It addresses whether we can consider bio-design and material innovation as a promising path for the future, explaining the evolving position of fashion designers who play a crucial role in this shift.

3.1. Bio-design and Fashion

Despite rising awareness of ecological crises, the fashion industry places increased emphasis on unsustainable practices linked to production and consumption. Bio-design is at the leading edge of future textiles and material innovations, combining the principles of biomimicry, bioengineering, and synthetic biology (Williams and Collet, 2020).

Bio-design is characterized as an innovative design approach that employs fundamental biological principles, extending its scope to encompass the integration of living materials into constructing structures, objects, and tools (Myers, 2012). Since this approach underscores regenerative production models, the utilization of biodegradable materials, and circular economic models, thereby challenging the conventional carbon-intensive practices prevalent in the fashion industry and offers an opportunity to challenge the conventional models for sustaining planetary boundaries and human well-being that were mentioned in the first chapter. When nature, living beings, and their linked life cycles can be incorporated into design, a revolution in materials that is required can begin. Understanding the interconnectedness of all life with nature and with other life is to realize what it means to design in a genuinely biological and circular way, as McDonough and Braungart (2002) explain with their ideas of cradle-to-cradle design. Bio-design is

an emerging concept for the fashion industry. However, given the fast pace of fashion and the need for constant change, it can be said that bio-design is struggling to keep up with this pace, but maintaining this pace is perhaps something that contradicts the essence of bio-design. For this reason, considering the relationship between bio-design and fashion, it would be more appropriate to put it in a unique position apart from fast fashion in the related bio-design approaches. In this context, the potential of bio-design to solve the circular problems of the fashion industry on a long-term basis stems from the fact that it aims to create an entirely new system. Although the fashion industry has historically tended to be influenced by nature, it has generally been the adaptation of structural principles rather than the use of alternative materials. At this point, it would be necessary to reconsider the definition of bio-based within the framework of bio-design.

The term bio-based product refers to "products derived in whole or in part from biomass, such as plants, trees or animals (the biomass may have undergone physical, chemical or biological treatment)" (Biofabricate and Fashion for Good, 2020). Due to the harmful effects of traditional petroleum-based textiles on the environment, bio-based materials have been developed that are produced from naturally originating resources, using living organisms in the production process (Kirk-Othmer Encyclopedia of Chemical Technology, 2010). These bio-based materials can be bio-fabricated or bio-dyes obtained from biological sources such as proteins, bacteria, algae, fungi, and cellulose into textiles; however, while bio-based material innovations aim to challenge the current textile production model and eliminate the environmental and social consequences associated with the linear economy model of the fashion industry, as mentioned before they remain insufficient in the face of these extreme impacts. Some advantages include significant savings in water, energy, and carbon emissions, positively impacting the environmental and social impacts of the production and use circles of bio-based materials. For example, biobased synthetic fibers, in the production of which petroleum derivatives are replaced by vegetable oils, starches, and sugars, reduce the use of fossil raw materials and CO2 emissions into the atmosphere. They also have lower efficacy in biodegradation processes. Therefore, their disposal takes much less time than their actual use, thus helping to tackle environmental degradation (Ribul, 2021). Nevertheless, it is essential not to be misled to assume that bio-based materials are always suitable.

Regarding raw materials, bio-based textiles can be produced from sustainably harvested raw materials or waste from various industries and specially cultivated agricultural crops. Therefore, it is essential to consider where crops are grown and how they are processed and transported. Additionally, the large amounts of chemical fertilizers and pesticides used in agriculture represent another problem, as do large quantities of water that release pollution into the soil and waterways (D'Itria and Colombi, 2022).

The designer can also produce materials directly from living organisms. This can bring new responsive solutions and different forms of expression for design and fashion. Understanding the fabrication of materials as an alternative to today's linear economic model is essential. Given its compatibility with the principles of biology and circularity, this new approach could represent a convincing solution to the fashion industry's environmental and social challenges (Ragnoli et al., 2022).

While the term bio-fabrication emerged in the medical sector, it was later expanded and defined as "the production of complex living and non-living biological products from raw materials such as living cells, molecules, and biomaterials" (Mironov et al. 2009). Bio-fabricated materials, with their biological origin and potential to be circular in relation to the processes, are a source of major investment in the sector to increase the potential of these organisms as alternative sustainable materials in parallel with designers' material experiments.

Currently, a range of materials is being developed from plants and organic systems, from the reuse of agricultural or food waste to yarns made from orange peel, from the use of seaweed and to leather from grapes or apple peel. Examples include Isabella Bruski and Noah Silva's Flora Fur, a sustainable, biodegradable, non-animal fur made of milkweed and hemp (Figure 13), or Aleksandra Gosiewski's AlgiKnit (Figure 14), made from seaweed, which is entirely biodegradable (Franzo and Moradei, 2023).

Figure 13. Flora Fur made of milkweed (Source: circumfauna.org, 2021)

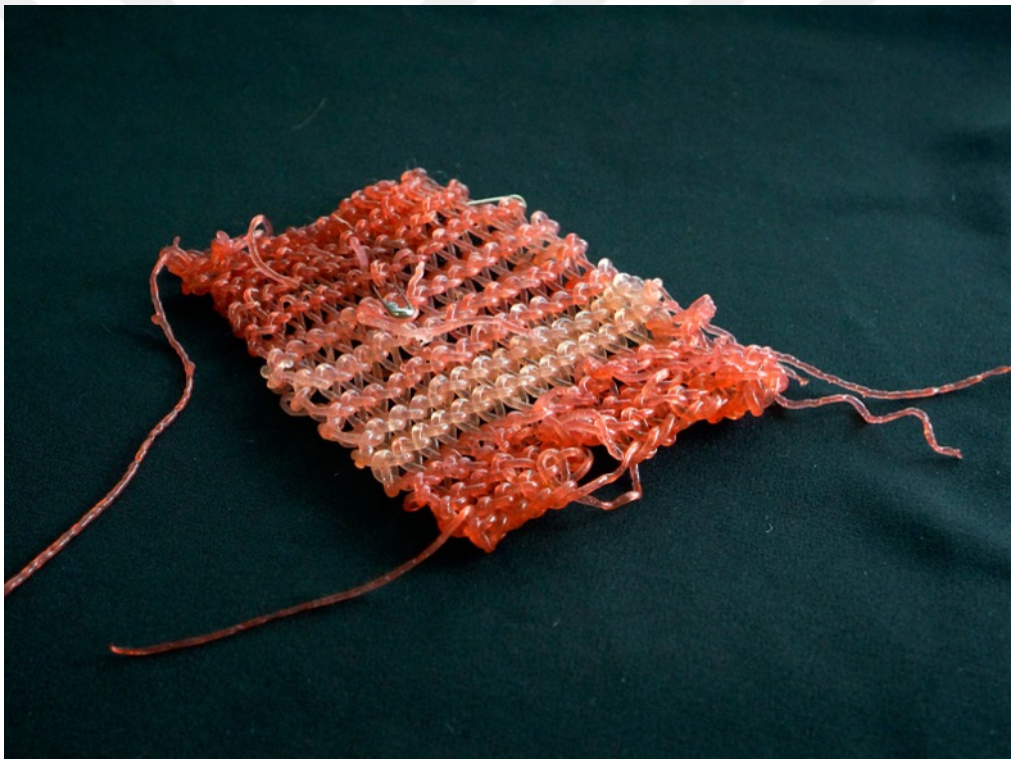

Figure 14. AlgiKnit's fibers are made by called alginate combining it with renewable biopolymers (Source: materialdriven.com, 2020)

Bio-design can also appear in a fashion product produced by a living organism needing care. Designer Roya Aghighi's Biogarmentry collection is produced from algae that photosynthesize the air and requires watering and attention at specific periods, just like caring for a plant (Aghighi, 2020) (Figure 15).

Figure 15. Biogarmentry, Clothes Made from Algae (Source: dezeen.com, 2019)

This is Grown by Jen Keane, which is one such organism-based approach that could help microorganisms replace synthetic materials. By developing a new form of microbial weaving by manipulating the growth process of K. rhaeticus bacteria, the material was produced by optimizing the natural properties of bacterial cellulose, which is stronger than the leather-like material produced from bacterial cellulose by Suzanne Lee, one of the earliest examples in this field (Figure 16). The manufacturing process resulted in a composite material that is lightweight, transparent and possesses tensile strength comparable to that of its synthetic counterparts. The material offers considerable potential for customization and application in various industrial contexts, including high-performance composites and biomedical applications (Doyle et al., 2023).

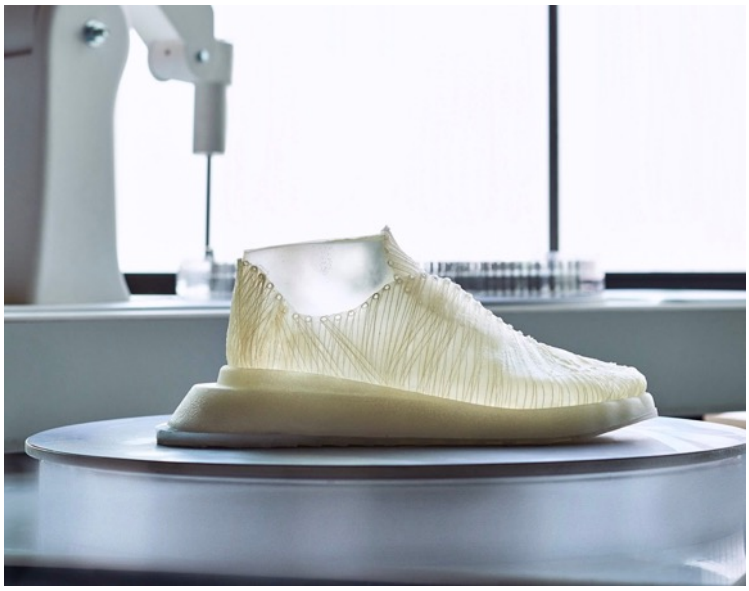

Figure 16. This is Grown by Jen Keane (Source: hreafta.com, 2022)

Other bio-design initiatives are reshaping the market; even luxury fashion brands are investing intensively in this area. Mylo, for instance, a truly innovative material that can be considered a new kind of leather. It's produced using 85% fungal mycelium and 15% lyocell, then finished with water-based polyurethane, which enhances its durability (Figure 17). This groundbreaking material has found its way into collections by fashion powerhouses like Stella McCartney and Adidas (Figure 18).

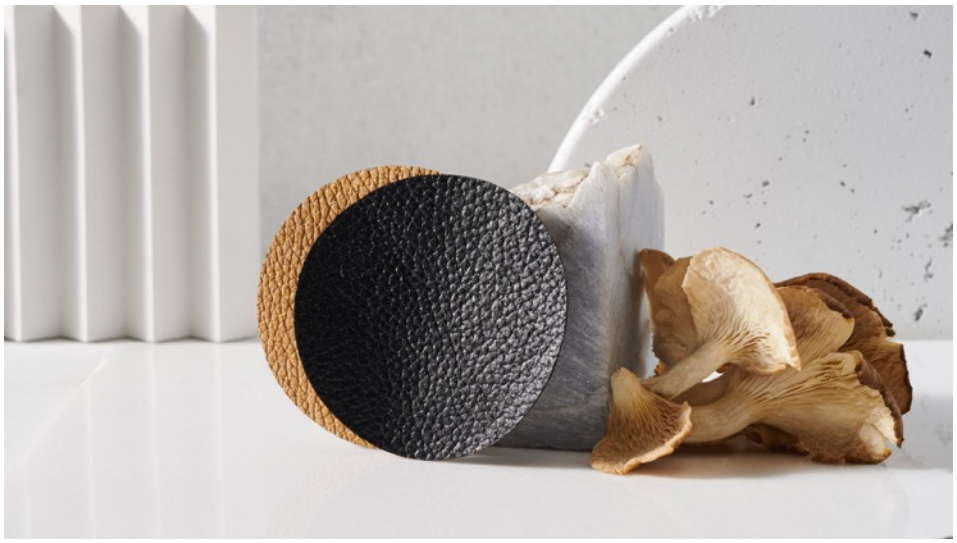

Figure 17. Mylo, a sustainable leather alternative made from mycelium (Source: www.dezeen.com, 2020)

Figure 18. Adidas' iconic model Gazelle reproduced with Mylo (Source: futurevvorld.com, 2023)

Moreover, BioSequins, bioplastic sequins made from tree cellulose by Radiant Matter, were developed as an alternative to the petroleum-based plastic options on the market that contain harmful chemicals (Figure 19). BioSequins are produced by first obtaining cellulose, then dissolving the cellulose into a gel like solution and allowing it to dry to form a thin film. These films are then chopped into small pieces that are as big as sequins. It also consumes less energy than the production of normal plastic sequins.

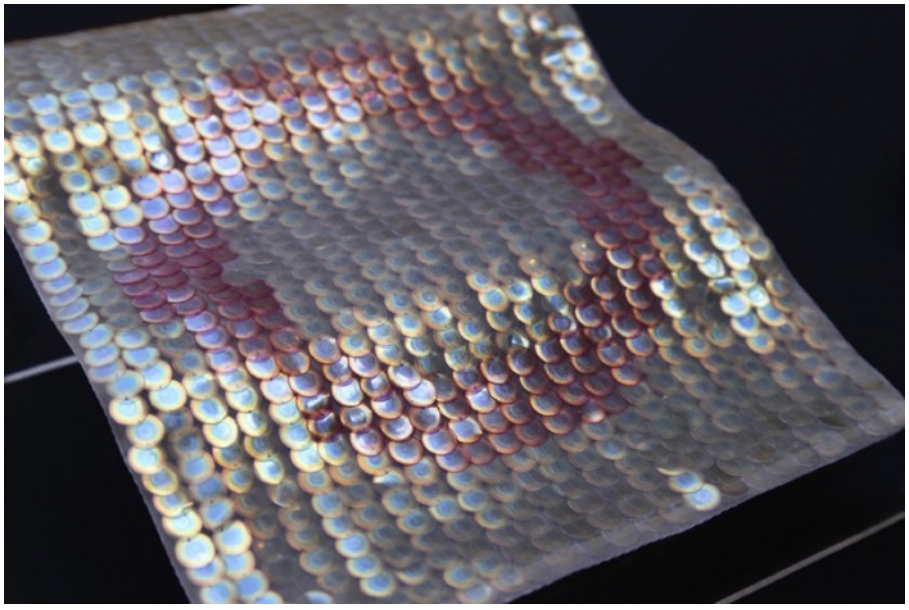

Figure 19. BioSequins, bioplastic sequins made from tree cellulose (Source: dezeen.com, 2023)

Recent experience with bio-based and bio-fabricated materials is characterized by a common perception that many of these materials are intended to replace and mirror many of the properties of their existing alternatives. Acknowledging the significance of the endeavor to generate alternatives, this emphasis misses the inherent potentials of numerous emerging materials, including vitality, impressionability, and responsiveness. These qualities are distinctive or innate to each organism (Barati and Karana 2019).

When we look at the examples of bio-design and fashion, they may initially appear as speculative material experiments. However, with the advancement of technology and ongoing research in this field, they are proving to be more than just experiments. They are becoming a tool to revolutionize the fashion design process, offering both aesthetic and functional capabilities that can meet the needs of the fashion industry. These functional capabilities, in turn, can indirectly benefit the health of our planet's boundaries and directly contribute to human well-being and a sense of flourishing.

3.2. Developing Circular Fashion Paradigm Through the Use of Bio-design

The fashion industry's environmental impact has been widely criticized for the waste it generates, the use of harmful chemicals, and the depletion of natural resources. Circular fashion is an appropriate model that considers the production and end of clothing products in its circle. Moreover, it ensures suitable materials are used to close this system (Niinimäki, 2017). The circular approach reduces the industry's dependence on resources and water usage. According to a report from the Ellen MacArthur Foundation (2017), approximately 63% of fibers or yarns used in clothing are sourced from plastics to produce synthetic fibers. When transformed into microfibers, these fibers threaten the ecosystem, mainly aquatic life. The report further suggests that the production of synthetic fibers from petroleum is expected to rise until 2050, consequently leading to an increase in the presence of microfibers in water.

Circularity and bio-design offer promising solutions to the environmental challenges of the fashion industry. Circularity focuses on designing products and systems that minimize waste and maximize resource efficiency throughout their life cycle. Bio-

design, on the other hand, leverages waste materials or self-reproducing living organisms to create environmentally friendly products (Thomsen et al, 2024).
In addition, bio-design uses renewable and biodegradable materials that can be more efficiently circulated through natural processes, which aligns with the principles of circular design.

While circularity also suggests a system in which materials are continuously reused, the continuous reuse of materials contradicts the fact that materials in bio-design are often produced to be short-lived and highly biodegradable. These biodegradability and composability principles encourage the development of bio-based and bio-fabricated materials that naturally degrade without harming the environment. These can be organisms that do not require land use or pesticides as they grow in salty seawater, such as brown algae, food waste that goes to landfills such as citrus or eggshells, ethically harvested oyster shell waste or plants, or mycelium that are grown through fermentation and decomposition process and require far less energy, water and other resources than conventional material production.

Bio-design and bio-fabrication are more efficient than other material production technologies, as they require less energy to harvest raw materials than conventional materials (Camere and Karana, 2018). The potential of bio-design, therefore, lies in rethinking fast fashion, for instance, by acknowledging and indeed slowing down the variable durations required by bio-fabricated materials, in contrast to the typical fast production process of the current economic model and seasonal fashion system (Collet, 2017). On the other hand, to overcome the inability of bio-design to challenge modern economic paradigms, it is argued that biodesign should help us identify new diverse biological, ecological, and social models that are fair not only for humans and particular cultures but for all biological entities (Ginsberg and Chieza, 2018).

Within the circular system, the role of the fashion designer becomes crucial. They are not just creators of aesthetic designs, but also key decision-makers in the choice of materials, production processes, and end-of-life strategies. Their decisions can significantly impact the environmental sustainability of the fashion industry.

3.3. Changing the Role of the Designer as a Scientist

Bio-design is not limited to designers' creative actions but encompasses the entire production process in which designers incorporate ecological concerns into the design.

An ecological mindset shapes the design process more than the outcome. This mindset aims at better integrating circularity and combining artificial and natural cycles more effectively. A key concern in bio-design thinking is to challenge a manipulative and instrumental process of engaging with non-human living systems and to recognize that these systems have their living capacities as actors in the world. This approach to design, which resembles the discipline's rejection of the conventional ontological distinction between nature and culture (Whatmore, 2002), as well as an interest in philosophies of plant thought (Marder, 2013), emphasizes a discourse of collaborating with nature rather than inferring from it, inviting all of us to be part of this transformative process.

Tacit knowledge in craft and textiles is used to experiment with living systems where a pivotal approach to working with nature is a coincidence, failure, and perhaps accident, and the practice here can be interpreted as conceptualizing production as ‘the flow and transformation of materials rather than final products’ (Collet, 2017). Bio-design, which combines biology with craft, always requires a slow and material-driven production process in the first phase due to the nature of the materials being collaborated with, even if some initiatives have moved to the industrial level.

In bio-design, the design focuses on creating experience and science on generating knowledge, but both progresses experimentally. However, bio-design processes are often non-linear due to inherent uncertainties.

In addition, it also has an aspect that works in collaboration with the material rather than leading it or even being guided by it. In this regard, it is helpful to consider the existing literature referring to Collet’s Framework Designing with the Living (2020), which presents guidelines for how a designer can engage with living systems. The framework is built on three hierarchies or categories of interaction between designers

and natural systems: nature as a model, nature as a co-worker, and nature as a hackable system. ‘Nature as Model’ suggests employing the best practices of nature norms that have been tried and tested to develop new solutions, meaning that designers borrow nature norms and adapt themselves to mimic and perform specific behaviors or functions found in nature. ‘Nature as a Co-worker’ is shifting toward a more cooperative manifestation as it deals with working alongside natural organisms. This method is closely related to techniques where a designer cooperates with living organisms like bacteria, fungi, or algae to design and control the emergence of the material. In this concept, the designer is like a gardener, creating the required conditions for the development and evolution of the organisms and letting them define the material’s outcome. The most revolutionary one is ‘Nature as a Hackable System.’ Designers can design organisms that would construct materials with a design gene program, which is only achievable with the help of synthetic biology. This approach can be explained as the process of changing the genes of fundamental life forms to create products to suit individual requirements. In this method, designers use synthetic biology to engineer organisms for biofuel, silk, and other products.

To establish a collaborative working relationship with a living organism, designers need to provide a suitable growth environment. That in turn, the living organism will produce a material or perform a function. This bio-design approach, with its transformative potential, requires an understanding of the mechanics of growth and a new set of tools and methodologies for design. The urgency of adapting to these new methodologies is clear. Designers can now grow their materials and manipulate their morphology as they grow, rather than relying on existing prefabricated materials (D’Olivo and Karana. 2021). Fashion designers are demonstrating that it is possible to go beyond the conventional boundaries of their disciplines in testing materials, hybridizing them with science, engineering, and biotechnology, and adopting an increasingly transdisciplinary approach (Oxman, 2016).

Whereas traditional form-oriented design has previously determined designers’ limited knowledge of materials, a shift is now taking place through direct action pushed by the designers themselves. Designers are now concerned with the conceptualization of the material, where the material becomes the real driver and

collaborator. With the emergence of a new paradigm of production based on cultivation and growth, driven by material innovation, and with biology becoming a tool for designers, this collaboration of design and biology not only challenges the status quo but also holds the potential to transform how we learn from and manipulate life and how we produce and consume products.

3.4. Enhancing Well-being Through Bio-design Inspired Textiles in Fashion

Beyond conventional pharmaceutical approaches, bio-design pioneers' innovative solutions that enhance individual well-being and contribute to environmental sustainability. The textile industry and research have been evolving towards new products and processes in recent years. Textile products are designed not only for aesthetic purposes but also to have technical properties. Furthermore, the new textile production process design considers ecological and environmental compatibilities. Considering the relationship between well-being and bio-designed textiles, it is clear that the existing literature is mainly shaped around smart textiles or wearable technologies. In addition, medical and paramedical textiles have received significant attention in various applications, including cosmetics, skincare, and thermal comfort improvement (Nelson, 2001).

While bio-design applications are currently at the innovation stage and not yet widely used commercially, the potential they hold is immense. Numerous applications are already taking inspiration from bio-design, hinting at a future where these innovations become mainstream.

One promising example is Mi Terro, which specializes in creating textiles infused with probiotics and transforms agricultural waste into high-quality, low-cost, and scalable biomaterials to end microplastics, using a variety of biopolymers and natural fibers to maximize the use of biomass (Biofabricate and Fashion for Good, 2020) (Figure 20). When it comes to incorporating herbs, SmartSilk produces bedding with a blend of silk and Aloe Vera fibers (Figure 21). Aloe Vera is known for its skin-soothing properties. Infusing these fibers into sheets and pillowcases creates a sleep environment that nurtures skin health and overall well-being. It is a good indication

that this type of textile can have an industrial counterpart in terms of being entirely commercial.

Figure 20. Mi Terro, Bioplastic from bio-mass (Source: awrd.com, 2021)

Figure 21. SmartSilk, Bedding From Silk and Aloe Vera (Source: smartsilk.com, 2022)

Beyond textiles and applications for wearable applications, Vollebak, an innovative clothing line, incorporates algae into its fabrics (Figure 22). Algae, a photosynthetic

organism, can capture carbon dioxide and release oxygen. By wearing these garments, individuals actively contribute to air purification, creating a microenvironment that promotes respiratory health (D'Olivo and Karana, 2021).

Figure 22. Biodegradable T-shirt Made From Plants and Algae (Source: www.fibre2fashion.com, 2020)

In addition, the Algae bodysuit SKIN SERIES, also a commercialized initiative, is knitted with therapeutic fibers (Figure 23). It claims to have antioxidant capacity by promoting cell regeneration from seaweed components.

Although it is stated that it is made from seaweed ingredients, it is not specified in which proportion, and the claim of well-being is a slightly superficial one since the product contains elastane in its material components, which is not very good when returned to nature. Further, it claims to strengthen the skin's immune system with its probiotic finish containing encapsulated bacteria.

Figure 23. Seaweed bodysuit, SKINSERIES (Source: materialdistrict.com, 2024)

In addition to being used in textile fibers, bio-pigment production and applications as part of bio-design are becoming increasingly extensive. Bacteria, yeasts, fungi, and algae are some organisms that typically produce natural colors (Agarwal et al., 2023). These pigments are essential for the innate ability of microorganisms to adapt to harsh environmental conditions and perform certain cellular functions. Such naturally synthesized pigments are used in various industries such as textiles, cosmetics, pharmaceuticals, and food due to their novel properties and advantageous properties that benefit human health and the environment (Agarwal et al., 2023). The most prominent example of this innovation is new dyeing applications in textiles, exemplified by the new technology of the Living Colourbio-design initiative. In collaboration with ArtEZ CoE Future Makers, Wageningen University and Research, and designers, they have conducted studies to improve the growth conditions and patterns, pigment quality, and color spectrum of bacteria (Figure 24).

Textile dyes derived from bacteria, offering a sustainable alternative to harmful artificial dyes, are not just a trend but a necessity. These artificial dyes, known for their detrimental effects on the planet and human health, are being replaced by bio-pigments in collaboration with sportswear brand Puma. The result is a collection of

various moisture-absorbent natural fibers that change color according to the season of the garment, highlighting environmental concerns and enhancing user experience (Figure 25).

Figure 24. Bacteria dye by Living Colour (Source: livingcolour.eu, 2019)

Figure 25. Design to Fade, Living Colour & Puma (Source: designtofade.puma.com, 2020)

Besides, the aspect of well-being and healing, which relates to bio-design, can also be using aromatherapy applications in textiles. The technology developed by a German-based textile chemistry company, Cognis, is known as Skintex. The process used in adding active ingredients into cosmetic textiles is known as microencapsulation. The active ingredients are encapsulated in microcapsules and tightly bound to the fibers inside the fabric without affecting the touch and visual appearance of the textile. Chitosan (a sugar from the outer skeleton of shellfish) is encapsulated to prevent heat, drying, and cold. It helps protect the skin from dehydration and maintains its elasticity and velvety soft touch. The beneficial components are either released due to friction during wearing, or the chitosan layer is slowly reduced over time by the action of the carrier enzyme (Ristić et al., 2022)

Table 4 provides a comprehensive list of the most prevalent applications of bio-design-inspired bio-based functional textiles. With their unique properties, these textiles contribute significantly to our well-being, offering a new dimension to textile technology.

Table 4. Summary of some common biological components used in textiles along with their possible well-being properties

Biological Component	**Source**	**Possible Well-being Properties**
Chitosan	Crab and shrimp shells	Antimicrobial, wound healing, promotes skin regeneration, hypoallergenic
Collagen	Animal connective tissues	Skin hydration, anti-aging properties, promotes wound healing
Seaweed (e.g., SeaCell yarn)	Seaweed	Antioxidant, hydrating, promotes skin elasticity, potentially detoxifying
Silk fibroin	Silkworms	Supports skin repair, anti-aging, maintains moisture, hypoallergenic
Keratin	Wool, feathers	Hair strengthening, skin smoothing, wound healing
Aloe vera	Aloe vera plant	Moisturizing, anti-inflammatory, soothing burns and cuts, accelerates wound healing
Bamboo charcoal	Bamboo	Odor absorbing, moisture-wicking, may offer UV protection
Milk protein (casein)	Milk	Hydrating, nourishing, may promote skin cell growth and repair

While the literature is primarily centered around smart textiles and wearables, research into medical textiles has gained attention, showcased cosmetics and skincare applications and improved thermal comfort. The intersections of health, sustainability, and technological innovation hint at a promising future for the textile industry and its diverse impact on human life and the environment. In bio-design, it is possible to analyze the social and cultural factors in creating medical and

therapeutic textiles. Moreover, exploring these factors within the bio-design can reveal ways of incorporating these new-generation textiles into everyday life as a means of promoting biodiversity at a local dimension. With a better understanding of bio-design, creating new materials using scalable and responsible technologies could indirectly provide a valuable collaborative strategy for reassessing biodiversity.

CHAPTER 4: EXPERIENCE SPACE FOR A BIO-DESIGN PRACTICE

As the boundaries between technology, ecology, and fashion become increasingly blurred, the practical applications of bio-design in the fashion industry need to be examined more profoundly. Therefore, this chapter highlights not only the theoretical frameworks discussed earlier but also concrete developments and real-world applications that underline the critical role of bio-design in sustainable fashion.

4.1. Seaweed-based Material Innovation

About 12,000 species of seaweed have been identified to date. Seaweed has been used in various fields for centuries, but especially in industrial applications since the beginning of the 20th century, reflecting its versatile properties and benefits.

In the food industry, seaweed has been an integral part of the diet in many coastal communities, particularly in East Asia. It is used in many dishes due to its nutritious content. Seaweed has been used in agriculture, where it serves as a natural fertilizer due to its mineral-rich and other growth-enhancing properties; coastal farmers in Europe and North America have used it to improve soil quality and increase crop production. It has been reported that iodine-containing seaweed has traditionally been used in Eastern medicine as a medicine for the treatment of goiter and other diseases, and today, it has been proven by different studies to have some antiviral, anti-inflammatory, and anticancer activities (Buchholz et al., 2012). Seaweed has been included in the cosmetic industry for skin treatment since prehistoric times, and today, extracts from seaweed are readily available in cosmetic markets due to its moisturizing and anti-aging nature (Pangestuti et al., 2021). Recently, seaweed has been evaluated as a renewable power source, and studies focusing on how to efficiently grow and convert seaweed for fuel production - seaweed biofuels - have begun (Jiang et al., 2016).

These very beneficial effects of seaweed have inspired various design fields in recent years. In architecture, seaweed has been explored as an innovative building material. For example, it has been used for insulation due to its natural fire resistance and thermal properties (Geß, 2021). In product design, designers have produced

biodegradable packaging and daily objects, such as bowls and cups, to reduce plastic waste and promote sustainable consumption (Waseem, 2023). Furthermore, seaweed-based materials have been used in interior design to produce eco-friendly furniture and decorative items (Jivkov, 2021). Apart from these, as previously mentioned in the literature, various applications have been made with seaweed and microalgae in fashion design (Figure 26).

Figure 26. The most prominent examples of seaweed and micro-algae collaboration in fashion design

Seaweed is among the popular biomaterials utilized in biomedical textiles because of the richness of biologically active compounds. However, the most common type is seaweed-derived alginates used in wound dressings and tissue engineering applications. These alginates create a hydrogel-aerated environment for recovery, which has hemostatic abilities that are important in controlling bleeding and encouraging tissue formation (Xie et al., 2022). In addition, there are fibers obtained from seaweed utilized in making nonwoven fabrics for wound dressing, whereby the antimicrobial features of seaweed are useful against infection (Tan et al., 2013). Moreover, carrageenan and other seaweed polysaccharides are also applied in the formulation of drug release systems that can enhance the pharmaceuticals' performance in terms of efficacy and safety (Chudasama et al., 2021). Although few

examples exist, using seaweed-based textiles in fashion beyond biomedical textiles to promote well-being and healing is not widespread.

Based on these inspiring applications, studies were carried out on obtaining biomaterial and natural dyes with an edible green seaweed species *(Ulva lactuca)* that is very common in our region's seas. Natural dye studies were also carried out by collecting seagrass, which is also abundant in our region's waters.

4.1.1. Designer Space: Harvesting, Production and Dyeing Experiments

Sea lettuce, commonly called Ulva lactuca, is a green, edible seaweed with several healing benefits. It is an excellent source of vitamins A, C, and E, as well as minerals iron, calcium, and magnesium, and it is an essential component in human nutrition and animal feed (Xu et al., 2023).

Sea lettuce is small but rich in content and contains high amounts of dietary fiber, which controls the gastrointestinal tract and aids in weight loss. The fiber contained in sea lettuce is influential as a bowel cleanser and characterizes low cholesterol and blood sugar details (Xu et al., 2023). Sea lettuce also contains potent antioxidant properties and thus helps prevent the formation of free radicals, which reduces the prevalence of diseases such as heart complications and cancer. In addition, these antioxidants, such as polyphenols and flavonoids, effectively minimize free radicals in the body (Ganesan et al., 2019).

As for the use of sea lettuce *(Ulva lactuca),* the agricultural industry is one of the most critical areas where this raw material is used. Loaded with nitrogen, potassium, and other fertilizers, lettuce can be used as a natural fertilizer to improve soil quality and promote plant germination. It also promotes the preparation of larger crops and other factors that make the farming practice sustainable regardless of fertilizer use. In addition, many studies on bioremediation have revealed that sea lettuce *(Ulva lactuca)* can be used as a remediation tool. (Türkmen and Su, 2019). They are highly useful in helping to protect the environment. They are used to remove heavy metals and pollutants from affected water sources. The properties that attribute to this are the high surface area and the ability to bind or adsorb pollutants in water (Abdulmajeed et al., 2014). Besides, the possibility of its use in biofuel production is

also being explored. Studies indicate that it can be retrieved in bioethanol and biogas, which can enhance the production of renewable energy, reducing the amount of fossil energy utilized and, hence, climate change (Jiang et al., 2016).

There are studies on the mechanical properties of sea lettuce *(Ulva lactuca).* Sea lettuce *(Ulva lactuca)* exhibits moderate tensile strength, the maximum stress it can withstand when stretched before breaking. This property is essential for creating durable films and fibers for textiles and packaging. Studies have shown that the tensile strength of materials derived from sea lettuce *(Ulva lactuca)* can be increased by blending with other polymers or by chemical modifications (Kowalski et al., 2020). The flexibility of sea lettuce *(Ulva lactuca)* allows the material to regain its original form after being compressed. Sea lettuce materials are relatively flexible and thus suitable when the end product envisaged is in the form of films and coatings. This property can be mainly applied in making biodegradable packaging materials where the packaging has to hold the content intact for a certain period (Dominguez and Loret 2019). Another feature of mechanical characteristics that can prove highly beneficial for sea lettuce *(Ulva lactuca)* is its biodegradable nature. Sea lettuce-derived materials disintegrate when exposed to the environment and thus count as eco-friendly compared to standard plastics (Bordeso et al., 2024). Furthermore, it can withstand prolonged physical stress and friction over time with various reinforcements. This characteristic renders them suitable for numerous industrial applications that involve textiles and bioengineering support structures (Satmalee et al., 2023).

In addition to sea lettuce *(Ulva lactuca),* seagrass, utilized solely for the extraction of dyes and dyeing experiments in this study, has yet to be subjected to comprehensive investigation regarding its properties. This is because seagrass is not classified as an algae species, which is a plant species. However, it is widely used in interior design to produce rugs, mats, baskets, and furniture such as chairs and tables. In some coastal communities, seagrass is used to make mats, baskets, and other handicrafts, providing a source of income for local artisans.

Within the scope of this study, firstly, sea lettuce *(Ulva lactuca)* was collected from the following location: İzmir Kent Ormanı, İnciraltı, Balçova. (Figure 27) The

harvesting phase was carried out ethically by collecting thoroughly washed-up on shore sea lettuce *(Ulva lactuca)* without removing the live ones (Figure 28).

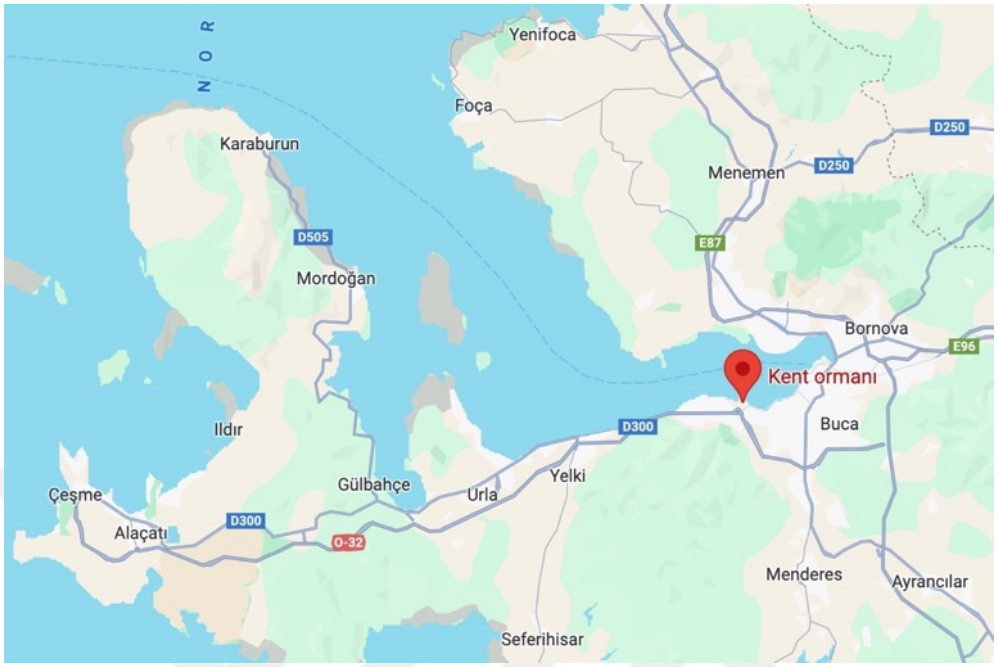

Figure 27. Sea lettuce (Ulva lactuca) harvesting location

Figure 28. Harvesting phase of sea lettuce (Ulva lactuca)

Seagrass only used for dyeing experiments was collected from Çaltılıdere, Aliağa region (Figure 29). This harvesting was also done ethically by collecting only the dried ones (Figure 30). Ethical harvesting methods involve accurately determining

which specific resources should be taken and how many should be taken so that the natural population of a given species is not depleted to the point of reaching a critical low (David, 2023). As research by Robinson and Zhang (2019) supports, ethical approaches to gathering and harvesting are beneficial because they act as an aspect of species and ecological stability, especially if strictly adhered to. Such measures include setting quotas, bans during certain seasons, or other less environmentally damaging prohibitions. Although present all year round, seagrass and sea lettuce in this study was collected in spring.

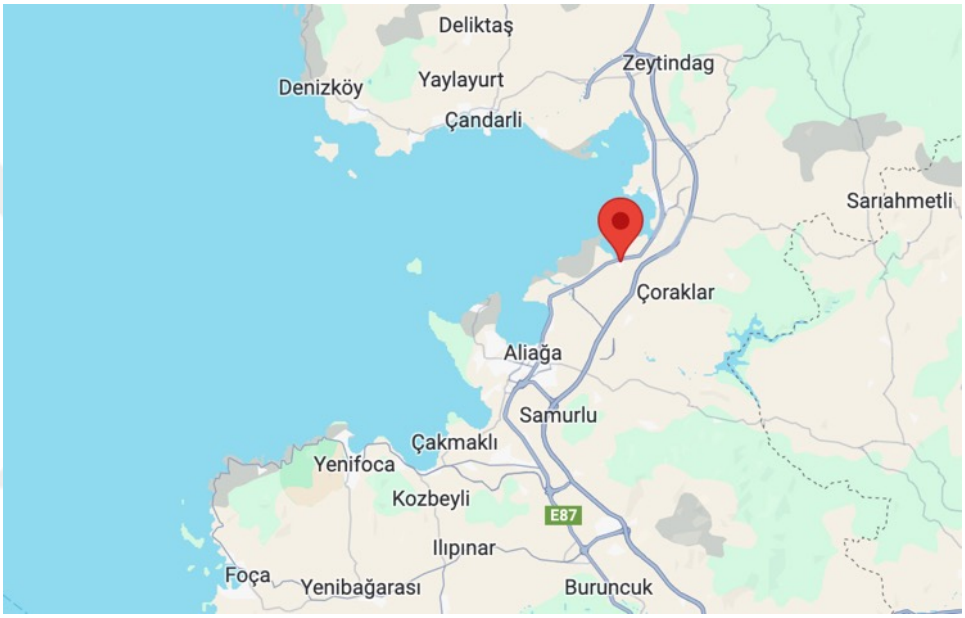

Figure 29. Seagrass harvesting location

Figure 30. Harvesting phase of seagrass

Firstly, bioplastic trials were carried out using three formulas from the harvested sea lettuce. Since there is no recipe for producing bioplastic directly from green seaweed or sea lettuce *(Ulva lactuca)* in open sources, a bioplastic recipe containing agar agar (from materiom.org) was tried separately with the sea lettuce *(Ulva lactuca*) and pectin added versions.

Accordingly, the sea lettuce *(Ulva lactuca)* was washed, sorted and drained and mixed with agar agar, glycerin; pectin, glycerin; pectin, agar agar, glycerin to obtain the most usable of these ingredients and to observe the changes in the material structure (Figure 31).

Figure 31. Production process of sea lettuce (Ulva *lactuca)* bioplastic

For bioplastic production, the washed and drained sea lettuces *(Ulva lactuca)* were mashed by a mixer and divided into three groups. In the first group, agar agar, one of

the conventional bioplastic production methods, was mixed until the water boiled, and then added glycerin. When it started to wax, it was allowed to cool slightly, and mashed sea lettuce *(Ulva lactuca)* was added. In the second group, mashed sea lettuce was mixed with pectin and glycerin in a ratio of 1:3, and a paste-like mixture was obtained by mixing. In the last group, pectin was added to the mixture of agar agar and glycerin at a ratio of 1:3 as in the first group.

Bioplastics obtained with three different ingredients are shown below (Figure 32). If these bioplastics are intended to be used as a textile surface, sea lettuce *(Ulva lactuca)*, agar agar, and glycerin contents were the most suitable for both flexibility and thinness. In addition, this material could be sewn together quite easily with an industrial flat stitching machine (Figure 33). The material containing sea lettuce *(Ulva lactuca)*, pectin, and glycerin does not seem very suitable for textile applications as it will be difficult to shape. The last ingredient, sea lettuce *(Ulva lactuca)*, pectin, agar agar, and glycerin, was molded due to the interaction of pectin and agar agar.

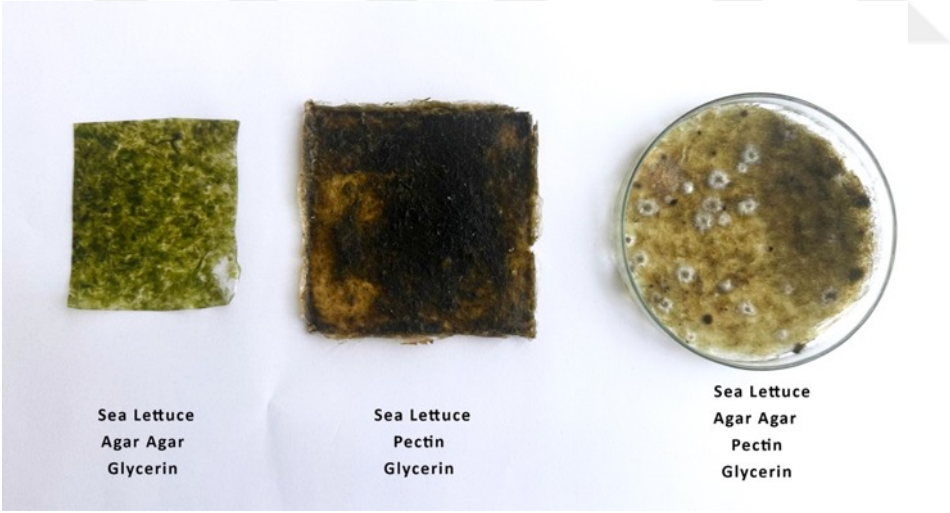

Figure 32. Different bioplastic trials with different ingredients

Figure 33. Stitch trial on sea lettuce (Ulva lactuca)

The extraction of dyestuff from sea lettuce involved two trials. In the first trial, SeaCell™ fabric, which was pre-mordanted with potassium aluminum sulfate and iron sulfate and kept in mordanted water for 24 hours, was again soaked in boiled sea lettuce water for 24 hours the next day. Dyeing recipes are given in Table 5. However, the conventional dyeing method using sea lettuce (*Ulva lactuca)* did not give results due to the chlorophyll content of sea lettuce (*Ulva lactuca).*

Table 5. Different recipes for dyeing with sea lettuce *(Ulva lactuca)*

Mordant	Mordant Amount (gr)	Material Amount (gr)	Fabric (gr)	Water (Liter)
Potassium Aluminum Sulfate	3	300	3	1
Iron Sulfate	0.8	300	3	1
Iron Sulfate	0.12	500	3	1

Since it is impossible to obtain dyestuff from sea lettuce (*Ulva lactuca)* by the indicated method, the following solvent method was used for the subsequent trial based on a study by M.I. Ab Kadir et al. (2014).

Firstly, 500 gr of sea lettuce was washed, drained, and dried at room temperature for five days. Then, it was crushed with a mortar and pestle and divided into small pieces. These tiny particles were kept in 0.4 liters of ethanol solution in an airtight environment for four weeks by steaming hot water twice a day, and then the particles were filtered through filter paper. (Figure 34).

Figure 34. Process of the extracting dyestuff from sea lettuce with solvent

As in the previous experiment, SeaCell™ fabrics of the same weight (3 gr) were pre-mordanted for 24 hours using 3 gr potassium aluminum sulfate, 0.8 gr, and 0.12 gr iron sulfate and then dyed by warm brew method using the dyestuff obtained by the solvent method. The reason for dyeing the fabrics by warm brewing is to prevent the ethanol-containing dyestuff from contact with heat and to prevent shrinkage of the fabric. At the same time, dyeing was carried out using the conventional boiling method with seagrass. The results of fabrics dyed with seagrass and sea lettuce (*Ulva lactuca)* in the second trial are shown below (Figure 35).

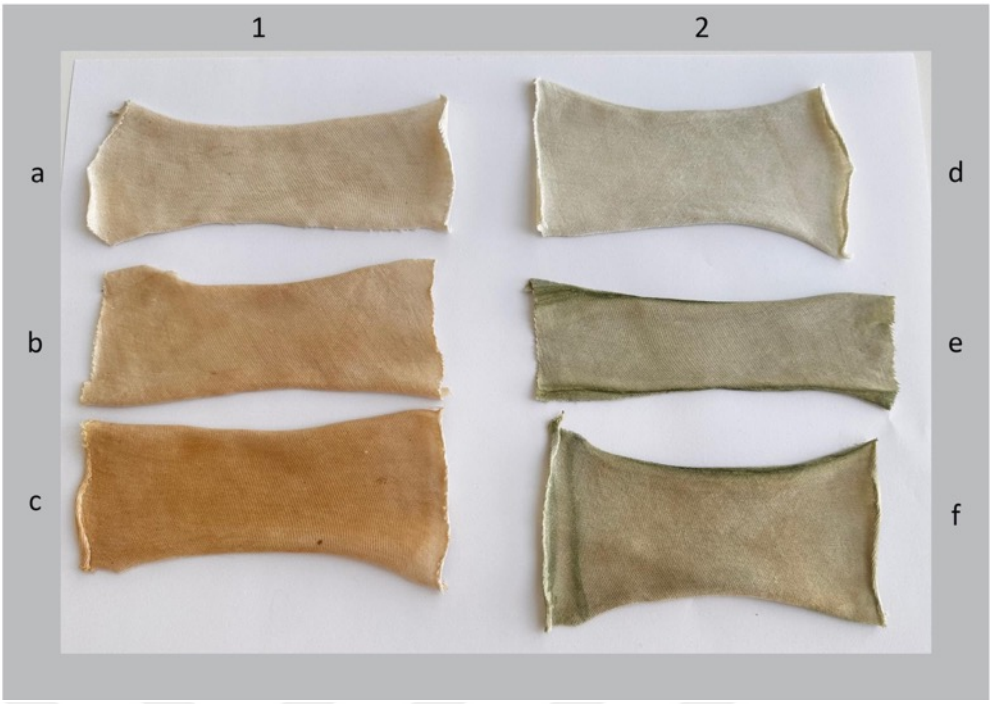

Figure 35. Dyeing results of seagrass and sea lettuce (Ulva lactuca)

Set 1 shows dyeing with seagrass and set 2 shows dyeing with sea lettuce. The amount of water used is 1 liter for each recipe, and the mordanting contents and dyestuff amount are as follows; 1a: potassium aluminum sulfate (3 gr), dyestuff (200 gr); 1b: iron sulfate (0.8 gr), dyestuff (200 gr); 1c: iron sulfate (0.12 gr), dyestuff (200 gr); 2d potassium aluminum sulfate (3 gr), dyestuff (100 cc); 2e: iron sulfate (0.8 gr), dyestuff (100 cc), 2f: iron sulfate (0.12 gr), dyestuff (200 cc).

Although dyeing studies with seagrass and sea lettuce *(Ulva lactuca)* have been considered successful, seagrass will not be used as this study is seaweed-based only.
The bioplastic trials in this study differ from the agar agar (gelatin alternative obtained from the cell walls of some red algae species) bioplastic trials primarily encountered in the literature. The few cases using psycho-chemical tests with sea lettuce (Bordeos et al., 2024) show that the material has potential. According to European standards (EN 13432) - when exposed to an environment rich in carbon dioxide, the material should degrade by at least 90% within six months, and in contact with organic materials, after three months, the material should degrade by at least 90% to sizes smaller than 2 mm. (EEA, 2020) - for the rate of biodegradation expressed in minimum thickness. In the tests carried out in the soil, the material

proved highly biodegradable, having decomposed by 82 and losing 5% of its weight in 21 days (Bordeos et al., 2024).

Although the study of Bordeos et al. (2024) provides much data on the material's properties, it will differ in each recipe, as in this study, since the sea lettuce species are different. The recipe and proportions of this bioplastic will affect the material structure. While material tests were carried out outside the scope of this study, it is clear that strength tests should be carried out with the potential for future use in the field of textiles. In addition, considering the beneficial and healing properties of sea lettuce *(Ulva lactuca),* although antibacterial and antimicrobial tests of the material should be carried out, a specific focus group should be determined for its effect on the user, and data should be collected by gathering feedback after specific use (e.g., effect on the skin).

This study, which is not at the industrial level, is an indication of how local biomaterials can be incorporated into the design system through a circular process and then safely returned to nature. It has been found that sea lettuce *(Ulva lactuca)* often grows uncontrollably due to domestic wastes released into the sea, especially on the coasts of our country, and damages the marine ecosystem (Bianet, 2023). This shows the potential of sea lettuce *(Ulva lactuca)* to be used and circulated as a waste material without even having to be grown.

Natural dyeing studies have shown that natural dyeing with seagrass and sea lettuce *(Ulva lactuca)* offers the potential to ensure environmental well-being and the well-being of the user by following an ethical approach not only by the material of the clothes we wear also by the dyestuff. Both the production stage and the ingredients of the dyestuffs are clean, and they can be easily applied to the industrial level. After a while, although there was no fading in the fabrics dyed with the dyestuff obtained from seagrass, a visible fading was detected in the fabrics dyed with sea lettuce *(Ulva lactuca),* which revealed that in further studies, industrial-level fixation should be carried out for better adhesion of chlorophyll in the dye content to the fabric.

4.1.2. Industrial Space: Fabric Innovation

At this stage of the study, with the collaboration of Sun Tekstil R&D Center, SeaCell™ fiber, the advanced and long-standing example of the adaptation of seaweed to the industry, was supplied by the company. It is necessary to examine SeaCell™ fiber in more detail before moving on to the phases of fabric development.

SeaCell™ fiber is a bioactive textile type mingled with cellulose-based fibers by spinning operations accompanied by a seaweed-derived compound (Thangavelu and Subramani, 2016).

The generation of Seacell fibers entails the incorporation of seaweed particles into the spinning solution during the method known as the solvent-spin process of cellulose fibers, in which the seaweed particles distribute evenly throughout the cellulose matrix (Zikeli, 2006). The basic technology for the production of SeaCell™ fibers is the lyocell process, known for its environmentally friendly properties, which uses N-methylmorpholine-N-oxide (NMMO) as a solvent to dissolve the cellulose, which is then processed into fibers. This process is well known for producing fibers with high strength, durability, and biodegradability (Reddy and Yang, 2015). In addition, harvesting the fiber and manufacturing the fabric is part of a fully responsible production process (Figure 36).

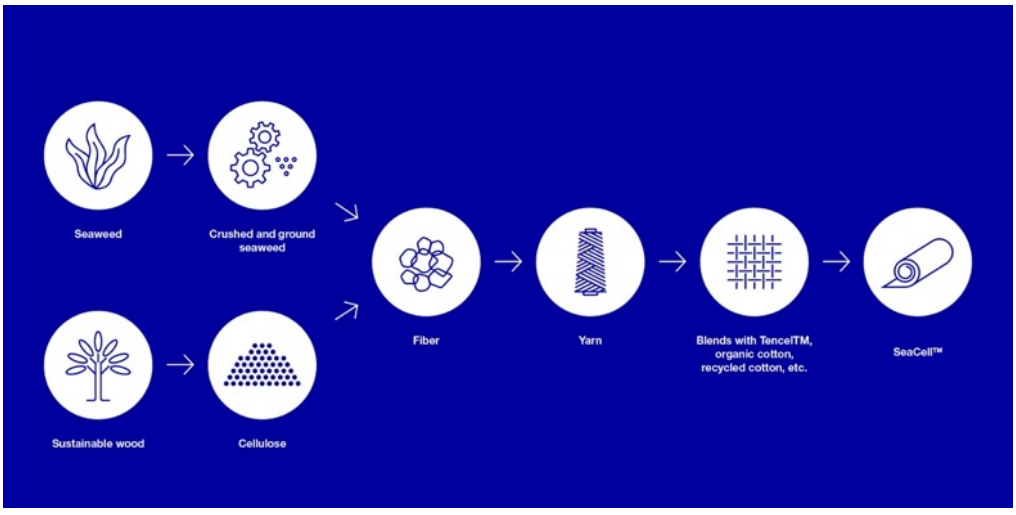

Figure 36. Responsible production process of SeaCell™ (Source: textilsantanderina.com)

Considering the mechanical properties of SeaCell™ fibers, it was found that they exhibit high tensile strength and good extensibility, similar to lyocell fibers. However, incorporating seaweed particles can slightly decrease these properties. Compared to other regenerated cellulose fibers, such as viscose and modal, SeaCell™ fibers show improved mechanical properties, including higher crystallinity and thermal stability (Veit, 2022). Incorporation of seaweed particles into SeaCell™ fibers improves their adsorption properties, which is beneficial for specific applications but may also result in increased moisture absorption. Chemical treatments, such as silane coupling agents, can increase the fibers' water resistance and dimensional stability, thus improving their mechanical properties under varying environmental conditions (Veit, 2022).

Composed of lyocell fibers and seaweed particles, SeaCell™ retains the physical properties of lyocell while incorporating the beneficial bioactive properties of seaweed (Janarthanan and Senthil, 2019). The fibers, especially those treated with silver nitrate, exhibit significant antimicrobial properties against various bacteria and fungi, including Candida albicans, Staphylococcus aureus, and Escherichia coli (Hipler and Elsner, 2006). SeaCell™ fibers also show good adsorption capacities for metal ions such as copper and zinc, attributed to the alginic acid-rich seaweed particles within the fibers (Hipler and Elsner, 2006). Known for their comfort properties, SeaCell™ fibers are suitable for applications in textiles that require good skin compatibility, such as socks, which provide better comfort compared to materials such as modal, bamboo, and cotton due to their skin-friendly and anti-inflammatory properties (Thangavelu and Subramani, 2016). Its applications range from medical textiles, where its antimicrobial and anti-inflammatory properties are evaluated in wound dressings, bandages, and garments for sensitive skin or skin conditions such as atopic dermatitis to functional garments offering therapeutic benefits (Hipler and Elsner, 2006),

Although SeaCell-included fabrics are widely used commercially, they are generally combined with materials such as cotton, lyocell, and elastane. The fabric's functionality is prioritized but needs to be reflected in the design.
Sun Tekstil R&D Center provided SeaCell™ fibers in two different compositions for this study. The first composition is 40/1 combed 75% pima cotton, 25% SeaCell™,

and the other is 80% cotton, 25% SeaCell™. Even though the fibers differ in content, a trial fabric was first knitted from both fibers to more accurately decide which yarn to use. A knitting machine in the R&D Center was utilized to knit small-scale sample fabrics (Figure 37).

Figure 37. Knitting machine and the knitting process of the fibers

This single-thread machine can knit fabrics with a width of approximately 18 cm (when opened) and infinite lengths. The two different fabrics resulting are shown below (Figure 38).

Figure 38. Fabrics knitted with two different compositions

Considering the advantages and disadvantages of the produced fabrics in terms of their use in the design, 75% pima cotton and 25% SeaCell™ composition fabric, which is more flexible, was selected primarily because flexibility was desired for the design to be applied in the next phase. In addition, the fabric containing 80% cotton and 25% SeaCell™ was not preferred due to its textured and slightly rough structure, as it may cause discomfort in contact with the skin and a chemical softening is not desired to be used within the scope of the study. Then, Sun Tekstil R&D Center knitted the rest of the fiber, and a part of it was used in the dyeing trials, as mentioned in the previous section.

4.2. Application of the Material in the Fashion Design

Application of the Material in Fashion Design section is divided into two as Sample Design and Pattern-making and Sewing.

Since the fabrics to be used within the scope of the study were knitted with a sample knitting machine and had a limited width, the product design was shaped accordingly.

4.2.1. Sample Design

Considering the beneficial properties of SeaCell™ fiber mentioned before, it was considered appropriate to design it as the initial layer in contact with the human body. This idea also led to selecting a stretcher fabric in the previous stage. Initially, the design had two criteria: shaping the design according to the width of the fabric and forming it into the body.

In the design phase, first, contemporary fashion research was carried out, and a fashion research board was prepared for the required shapes and details (Figure 39). Then, finding practices were conducted with AI-generated sketches (Figure 40). The dyeing trials previously carried out with sea lettuce (Ulva *lactuca*) were applied to all fabrics during the design process. The solvent-based dyeing recipe with code 2e from the previous dyeing trials was used.

Figure 39. The fashion research board

Figure 40. AI-generated sketches for initial ideas, generated by Skecth plug-in Chat GPT4

After the sketching and discussions with Sun Tesktil R&D department, it was decided that the most appropriate model was as follows, and suggestions for sewing details were presented together with the technical drawing (Figure 41).

Figure 41. First technical drawing and stitch types suggestions

The aim is to achieve a form that will fit the upper body and make the user feel comfortable, as much as the width of the fabric allows, and for this reason, the pattern pieces in the design mainly follow the anatomical lines of the body.

4.2.2. Pattern-making and Sewing

Sun Tekstil's pattern-making department carried out the design's pattern-making phase. However, when cutting fabric according to the pattern, it appeared that the already limited width was shrinking more than expected despite using the warm brewing method during fabric dyeing, so the first pattern-making study was canceled. Based on this, the panels on the model were reworked (Figure 42), and the fabric was dyed again for use in this new design.

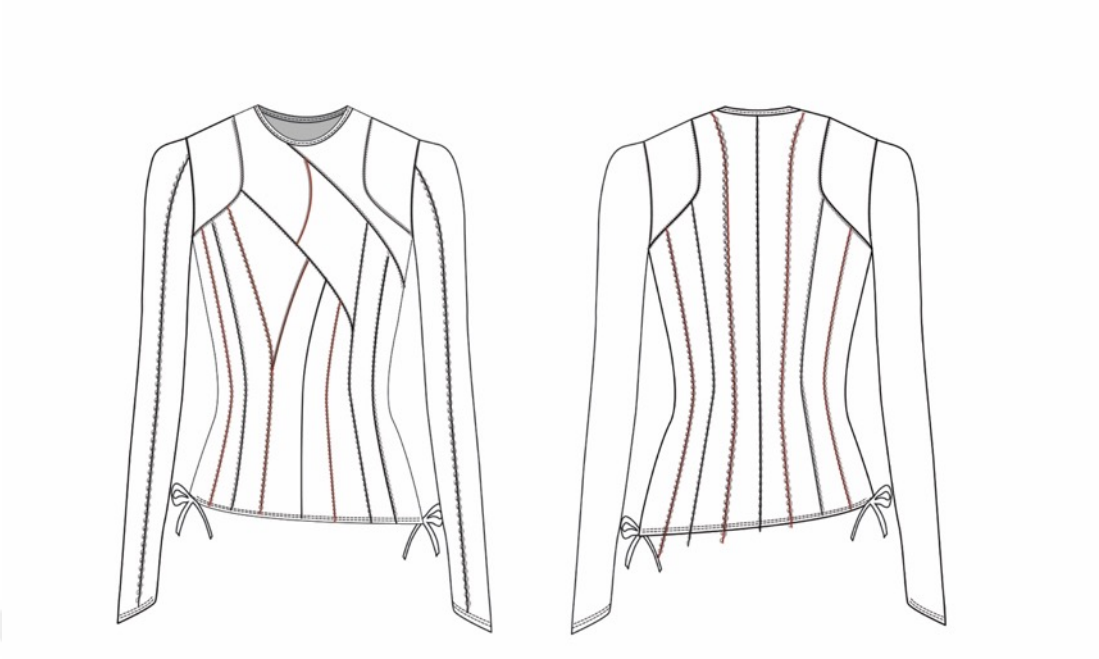

Figure 42. Design improvement and second technical drawing

The company made the pattern for this new design (Figure 43). Since the aim was to ensure sufficient width of the fabric, the pattern pieces were divided into as many pieces as possible without changing the design excessively, especially in the vertical direction.

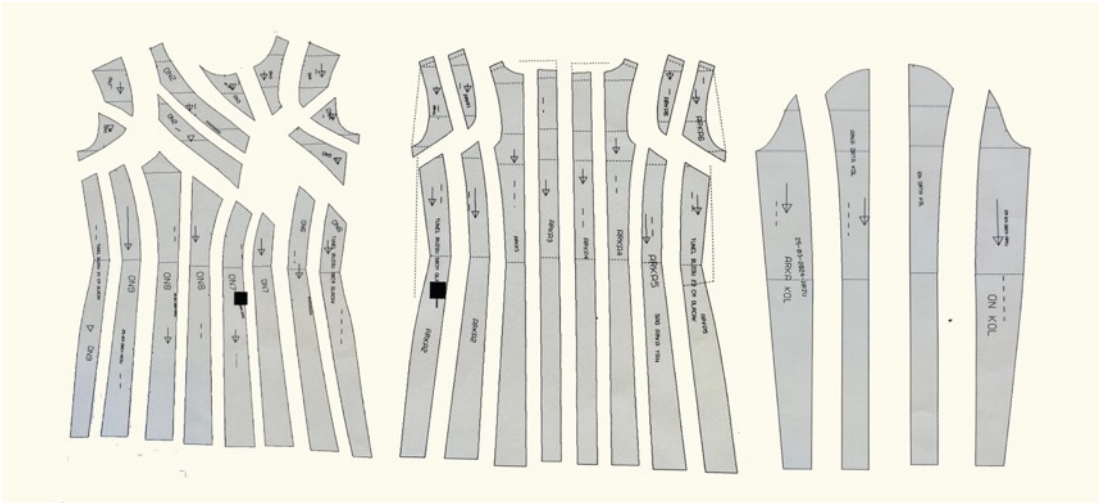

Figure 43. The front, back and sleeves patterns of the new design

After the preparation of the new design, pre-dyed fabric pieces were taken to the cutting process (Figure 44).

Figure 44. The cutting process

After cutting, the production process consisted of the following steps: arranging the pattern pieces (front, back, and sleeves), sewing the pattern pieces together with overlock, finishing the sewn pieces with flatlock stitching, preparing binding for the neckline and sewing the neckline, assembling the front, back and sleeves and ironing. As the pattern consists of multi-pieces, the pattern pieces are first organized to understand which parts are to be assembled (Figure 45).

Figure 45. Organization of pattern pieces

After the adjustment of the pattern pieces, the pieces were assembled with a 5 thread overlock machine and then the parts were stitched with flatlock stitch (Figure 46).

Figure 46. 5 thread overlocking machine assembled pieces, stitching with flatlock machine, flatlock stitched fabric sample

As the production stage proceeds, first the front pattern, then the back pattern and finally the sleeve pattern pieces are assembled internally (Figure 47).

Figure 47. Assembled front, back and sleeve pieces

After the front and back patterns were assembled, the binding prepared from its fabric was attached to the neckline with a binding machine (Figure 48). Finally, the sleeves were sewn to the body, and tunnels were prepared on both sides with a regular stitch machine (Figure 49).

Figure 48. Attaching binding to the neckline with binding machine

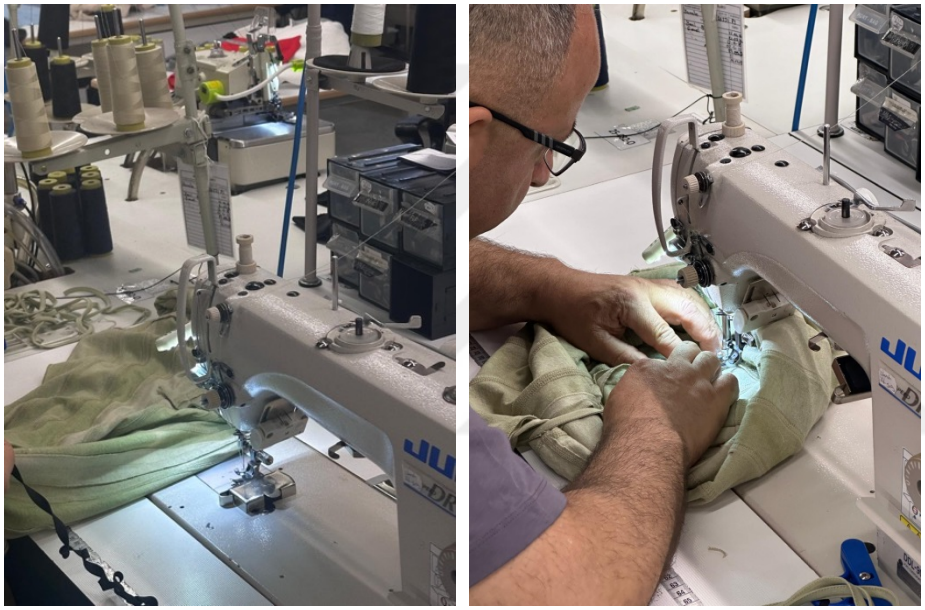

Figure 49. Sewing of the sleeves and preparation of tunnels

Figure 50. The front and back photo shooting of the finished product

After these phases, the finished product passed through quality control like the other samples in the Sun Tekstil sample production line, the threads were cleaned, ironed and photographed both front and back (Figure 50) and details on the dummy (Figure 51).

Figure 51. Detail photos of the finished product

This garment, designed in many pieces due to the need for more fabric width, created shrinkage at some points due to the pattern pieces' high number of joining points. Nevertheless, since the pre-sewing planning of this garment, which took 2.5 hours to sew, was planned carefully before sewing, the production speed required by fast

fashion was close to the production speed of the given design in the scope of this research. In addition, the tonal differences in the fabrics, which became more apparent after the pieces were assembled, were caused by the chlorophyll content of the dyestuff, even though the same recipe was used for dyeing, and showed fading in some areas over time as they contacted with air.

CHAPTER 5: CONCLUSION AND DISCUSSION

This study first identifies the vital link between planetary boundaries at risk and environmental well-being, laying a foundation for understanding well-being through the lens of body and clothing. The study examined a variety of design contexts (particularly biophilic, emotional, and sustainable design) to show how this concept of well-being is more widely and explicitly addressed in fashion compared to other design fields.

Research examining the fashion industry highlights the dynamic interplay between the female body, fashion, well-being, and significant societal changes brought about by historical events and cultural trends. It then examines the role of sustainable textiles, material innovation in circularity, and the analysis of selected bio-based materials. It highlights that while these materials are marketed for their environmental benefits, their actual impacts and production processes can be complex and nuanced.

The focus then shifts to bio-design, identified as an important element of the study. The integration of bio-design with fashion is explored through innovative initiatives and practices that embrace the principles of circularity and innovation. This chapter points to the changing role of the designer, who now acts as a collaborator and scientist rather than a mere creator, driven by the need to develop materials and processes that do not harm the environment and promote well-being.
Practical applications of these concepts are exemplified through the use of seaweed-based materials, particularly in the production of bioplastics and dyestuffs from sea lettuce and seagrass. The research outlines experimental processes from harvest to dye production, revealing limitations such as the poor durability of dye obtained from sea lettuce using the solvent method.

During the industrial application phase, the SeaCell™ fiber was provided by Sun Tekstil's R&D department. The fiber was chosen for its environmentally responsible production and potential well-being benefits. The study explained the detailed process from knitting and dyeing to final garment production. It ends with practical

difficulties encountered, such as shrinkage during the dyeing process, which requires adjustments at the pattern-making stage.

Overall, this study provides a better understanding of how bio-design and circularity can be oriented towards fashion design, paving the way for an environmentally sustainable and healthier industry. It underscores the need for further technical and economic feasibility research to develop seaweed-derived materials for commercial-scale traditional fashion. Additionally, bioplastics derived from various seaweed species need to be tested for durability and functional incorporation into traditional fashion products. The study also emphasizes the importance of increasing the acceptability of such materials among consumers and policymakers to establish them as a norm in the fashion industry.

This existing research needs to be followed by future research investigating the potential utilization of biomaterials and other technical challenges affecting their implementation on a large scale. As part of this study, bioplastic trials should be continued at a scale where they are brought to product level. It is, therefore, more accurate to evaluate the potential of this material in textile applications when tests such as durability, moisture retention, and tensile strength are applied. In the case of SeaCell™ fabric, conducting a more comprehensive study on their effect on users and how they feel beyond the material's responsible production and beneficial properties would be helpful.

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