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Markers and signatures methods on textile materials – the possibility of evidence led manufacturing chain and possible uses in the context of textile recycling

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ABSTRACT

A green image is becoming increasingly important for companies in the textile industry and recycling textiles is a problem because fibers are difficult to identify and therefore difficult to recycle. Especially the cross-linking of DNA and textile materials can achieve a significant benefit within the textile industry. In addition to DNA markers, alternatives like cryptographic marking, RFID technology, and other innovative approaches will be discussed. Markers and signature methods on textile materials are important for efficient recycling processes, but this topic has not yet been sufficiently researched. This review gives an overview of ongoing activities on signature methods and recycling approaches for textiles and focuses on the recycling of garments to address the challenges and solutions within the textile- and fashion industry.

Keywords
recycling,
DNA marker,
textiles,
counterfeiting,
textile marker,
traceability,
supply chain,
counterfeiting,
blockchain

1 Introduction

The results of the latest studies in the field of textile industry perspectives show approaches that go hand in hand with the preceding considerations of this review. The Textile Research Board's study on prospects for 2035, published in March 2020, analyzed how the textile industry can develop until the year 2035 [1]. In line with the aspects that we intend to address in this present report, the said study prioritizes the following research regarding sustainability. It is postulated that in the next 15 years, there will be a worldwide increase in the consideration of sustainability issues in all industrial sectors. As consumers' awareness of environmentally friendly production increases and appropriate recycling processes of products are on the rise, they are to be established as standard procedures. Politically, resource-saving production is to be taken up further and enshrined in law [1-2]. Due to this recognizable trend, many new and supposedly sustainable products are entering the market. However, this also gives rise to problems like greenwashing, making it difficult for consumers to distinguish whether a product is actually sustainable or only appears to be so. Nowadays, consumers and product manufacturers alike often cannot tell exactly where a raw material comes from. In addition, after the end of their lifecycles, the textile products should ideally be reused to protect the environment and save resources, as a lot of water and chemicals are used to produce natural fibers and petroleum by-products are used to produce synthetic fibers [3-5]. To solve the problem of untraceable routes of raw materials, some innovative approaches are now being advanced, e.g. DNA markers, cryptographic markers, RFID technology and others [6-7]. With the help of these innovative ideas, greenwashing and counterfeiting in the textile industry could be combatted. Today's textile products are complex and highly functionalized and are produced not only with traditional processes but also with new technologies such as 3D printing on textiles or the integration of electronics and components into textile products [8-9]. This complexity of the products, which are often composed of different components, makes it difficult to identify the individual parts, e.g. the raw materials such as fibers or electronics, and increases the problem of recycling at the end of the product life cycle [10].

This review looks at innovative textile marking solutions that can help to combat systematic greenwashing. Finally, it gives a brief outlook on which companies already offer solutions for marking textiles and which innovative ideas could be developed further. It also shows how textile markers can be integrated into recycling to counteract the problems associated with waste disposal and the possibility of the evidence-led manufacturing chain. The marker technologies were identified through a comprehensive literature review using specific keywords such as 'textile marking', 'recycling methods', and 'technological innovation in the textile sector'. The research was conducted in academic databases like Scopus, Web of Science, and Google Scholar. Additionally, a patent search was conducted in the World Intellectual Property Organization (WIPO) database to address patented techniques. The aim of the review is to provide an insight into textile labelling in the textile industry as well as an overview of which ideas are already available on the market.

2 Markers, signature methods and traceability technologies

The identification and traceability of textiles are also justified in other areas of application. Signature methods are needed for the authentication of brands as well. For the most part, the trustworthiness of products is based solely on the textiles' original labels. To combat counterfeiting, research is also being done on RFID labels [11]. Electronic components are attached to or sewn inside the textiles and interact as memory and radio transponders. Radio signals enable data to be transmitted even over short distances. In addition to innovative technologies that require a high level of financial investment, research is also being conducted into cryptographic techniques, among other things [12]. This type of signature, for example, makes identification possible without the need for additional devices or the understanding of complex physics. Accordingly, this cryptographic method is also used for the production of digital signatures and thus illustrates individual integration. Asymmetric key cryptography consists of two related keys: one public and one private key [13]. In the case of textile fabrics, the identification can be carried out with a string of characters. With the help of the public key, it is also possible in this type of application to guarantee trustworthiness to the consumer [14]. In some cases, fluorescent rare earth is applied to textiles, emitting an ultraviolet color that is invisible to the naked eye. With this technology, the product itself is neither chemically nor physically altered [15]. Another option would be to mark textiles with coded yarns. In this case, special yarns are woven or knitted into textiles, which then act as the information carriers [15]. A similar method would be the integration of fluorescent nanofibers. These are wrapped around the surface of core fibers during electrospinning and then also serve as the carriers of information [16].

The textile marker technology is used to implement the main three themes on which the company focuses. First, complex global supply chains are to be made more transparent. Second, it is to be made easier for companies to implement their sustainability requirements. And third, products should be able to be certified as original. For example, SigNature® T Textile Brand Protection from the company Applied DNA Sciences provides a unique molecular marking, testing and traceability system for textiles [17]. SigNature® T method is applying a unique molecular DNA tag by using an alkaline activation for immobilization of DNA taggants in combination with a multimode image and spectral reader. The possibility of marking fibers, yarns, fabrics and garments that easily survive every stage of textile treatment processes and recycling can be carried out in this way. The proprietary signing with SigNature® T is designed to adhere well to any textile substrate, including natural and synthetic fibers, and make counterfeiting impossible [17]. The company Proneem uses rare earths with fluorescent properties in fibers that irradiate under a special UV lamp. This technology, called D.N.A. Textile^tm, facilitates quality control and identification of fibers in textile products [18]. The company Tailorlux GmbH uses similar technology and integrates inorganic pigments into carrier materials such as polymers, paints, adhesives or liquids to give the product an individual optical fingerprint. In addition, the key-lock principle is used to ensure the security of the marking, which is invisible on the product, forgery-proof and can be used in court [19]. The company Grafe Advanced Polymers GmbH uses pigments that are designed to be highly complex with special physical properties in order to mark products. The markings can be easily and quickly read and authenticated using a calibrated detector. In addition, two authentication solutions are offered with X-ray or light fluorescence detection [20]. The company TextileGenesis™ offers pigment, DNA marker or isotope mapping for yarns and textiles made from fibers and uses blockchain technology to verify and make transparent the use of sustainable fibers at all stages of product manufacture from fiber to finished product. This blockchain technology has the advantage that all steps of the production of a garment as well as locations of farms, factories and facilities are documented in an ID and are easily traceable. In addition, the company has launched a pilot project with H&M in 2021 to test the traceability technology of TextileGenesis™ and develop new products [21,22]. In this context, it should be pointed out that blockchain technology can also be flawed. In this application scenario, for example, incorrect information can be entered and this aspect should be taken into consideration and optimization potential created. Table 1 provides an overview of the current technologies in the field of marking. The technological status is also explained and, where applicable, systems that have already been patented are listed.

Table 1. Overview of developed technologies for marking textile fibers.

Company	Technological state	Related Patents	References
Haelixa, Switzerland	This technology is using molecular code systems which can be applied in a storage method for nucleic acids. The invention further relates to specific particles, in particular silica encapsulated DNA particles, and to their use in secure marking.	EP2831268A1	[23,30,31]
SigNature® T, USA	Marking is done by alkaline activation for Immobilization of DNA taggants in combination with an multimode image and spectral reader.	US 2014/0256881, US 2016/0246892	[17,24, 25]
Proneem, France	Traceability and control system D.N.A Textile^{tm} based on assembly and integration of rare earths with luminescent properties. DNA is fixed in the fibers and amit specific colour under UV light.	n. a.	[18]
Tailorlux GmbH, Germany	Tailor-Safe integrate anorganic pigments in the product which leads to a machine-readable identification. Temperature resistance of up to 1,700°C.	GB2592691	[19,26]
Grafe Advanced Polymers GmbH, Germany	Special markers form the basis with highly complex pigments and special physical properties. Detection via x-ray or light fluorescence.	WO2013091623A8	[20]
TextileGenesis™, Netherlands	Fibercoin™ traceability technology offers pigment, DNA marker or isotope mapping for yarns and textiles made from fibers. The corresponding blockchain enable fiber-to-retail traceability data protocol (based on GS1 standard).	Patent pending	[21,22]

2.1 DNA textile marking and potential applications

DNA markers are applicable on every possible material, meaning that they can be applied to natural fibers like cotton or silk as well as on synthetic fibers like polyester or polyamide [20-21]. In addition, DNA markers are applied to products to assign information to them – like their origin or their single process steps – and make them traceable through the entire supply chain [19-21]. DNA marker tracing can provide brands with the ability to maintain an overview of the origin of the different materials. In addition to the companies' desire to achieve more insight into their entire supply chain, there is also a growing sense of general end-consumer responsibility. End consumers are increasingly aware of the sustainability aspects of the goods they purchase. There is a growing demand for information on the materials used and the conditions under which the products were manufactured. This information can be made available to the consumer through companies that use DNA markers [2,21].

Not only do end consumers exert pressure on companies, but governments also hold them accountable. In Germany and on a European level, companies face increasing regulations that impose liability for failures and violations in their supply chain. The ban on Xinjiang cotton in the United States caused import difficulties for numerous companies as they were unable to sufficiently prove the origin of their goods [27]. Meanwhile, in Germany, the Duty of Care Act (Lieferkettensorgfaltspflichtgesetz, LkSG) [28] sets out explicit guidelines for companies to uphold human rights throughout their entire supply chain and designates authorities responsible for verifying compliance. Thus, it is possible to create an infinite number of different markers, meaning that every single product can be assigned a unique identity. The markers can carry any possible information [29]. One of the most common solutions for more transparency in supply chains has been the blockchain principle. With this principle, a decentralized database connects the various nodes of a supply chain. To achieve that, data records are cryptographically encoded and attached to other data records and thus stored in a verified manner. The digital transactions can thus be viewed and expanded by all participants at any time [30]. Even if the information carriers of the individual technologies differ, the information flow always follows a very similar principle, which is exemplarily shown in Fig. 1.

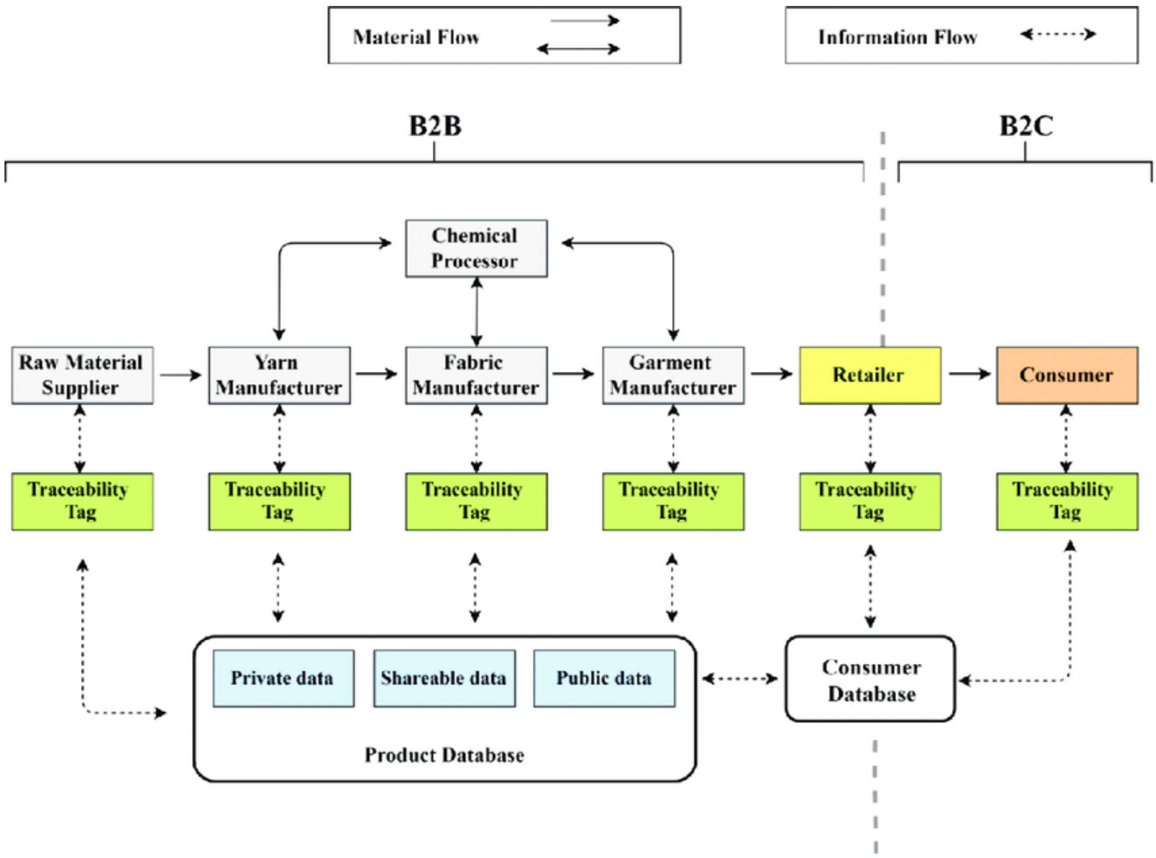

Fig. 1 The framework of textile supply chain traceability system [31], originally published under a CC.BY 4.0 license.

Inevitably, this method requires technology both at the marking level and in the area of the reading process. Nevertheless, the reliability can be classified as very high, not least because of the stability of the textile [14].

Using the example of the company Haelixa, DNA marking of textiles is presented in more detail in order to better understand the textile marking process. The company Haelixa is a Zurich-based spinoff of the Swiss Federal Institute of Technology (in German: Eidgenössische Technische Hochschule in Zürich (ETH)) [2] founded in 2016 by Michela Puddu and Gediminas Mikutis [32-33]. This Swiss company found an innovative solution that can be implemented with the help of deoxyribonucleic acid (DNA), which is integrated into recycling processes [32-33]. DNA-based solutions contain microscopic but detectable particles, usually with a size of about 1 mm. Embedding these micro-tags in raw textiles, raw fibers or the finished product opens up the possibility of identification at almost all stages of production [34]. Deoxyribonucleic acid acts as the carrier of genetic information for every living organism. It consists of nucleotides that are aligned with one another, creating a double helix. The combination of nucleotides is unique in every DNA and can be encoded and decoded [35]. This means that the DNA does not contain any genes and therefore cannot influence the materials in any way. On the DNA, a code is saved that is registered in a database and translated into any possible information. The markers from Haelixa are usually dissolved in a liquid, such as water or oil, and then sprayed onto the material. The amount of markers, and thus also of the liquid, depends on the volume of the material to be labelled. The liquid not only ensures that the DNA can be applied more easily, but also causes the DNA markers to combine with the material and adhere to it. In this way, the product itself becomes the information carrier. The spraying technology can either be integrated into other production steps or be done separately and even manually for small volumes [28].

Textile marking can be performed on the raw material as well as at any other step of the production chain, as witnessed in examples from Tailorlux, TextileGenesis^{TM}, Haelixa etc. [19-22,28]. Companies are using this textile marking technology to increase the transparency of the textile chain and to ensure anti-counterfeiting, and this need represents a new business model that allows companies to drive new developments in this area. Taking the example of cotton, the DNA could be applied at the beginning in the blow room but also later, for example during the spinning process. Using the example of cotton that has been DNA-tagged, this information can include the exact cotton farm, the manufacturer, and even the original cotton lot, allowing for a detailed look at all stages of the product's processing. Brands, manufacturers, and retailers can access this detailed information about the product at any time [19-22,28].

3 Recycling integration

General problems of recycling approaches in the field of textile recycling are known and possible solutions are being developed, but not yet used on an industrial scale [36-38]. In general, recycling of textiles is difficult primarily because it is not known which fibers the fabric is made of. Here, the identification of fibres and textiles can be of significant support. Approximately 97% of the global resources used in textile production are newly produced raw materials; with only 2% recycled raw materials from other industries and 1% recycled raw materials from textiles with the same or similar applications. It is important to note that this percentage of 1% is related to the residual waste generated during production [39]. According to the study "Textiles and Sustainability" by Bayern Innovativ, 67% of the experts surveyed stated that there is great potential in the fiber sector to develop more ecologically sustainable products through further technical developments and new technologies [40]. The experts see by far the greatest development potential in the area of finishing and recycling technologies. A functioning circular economy and close cooperation along the entire value chain are essential. The focus is on fiber recovery without loss of quality. At this point, the interviewee said, recycling only makes sense if material separation is possible and does not consume more resources than in conventional production [41].

3.1 Recycling routes of textile waste

A circular economy aims to lead textiles into a closed-loop. At present, the majority of textile cycles are linear (open-loop). Figure 2 shows these textile cycles, also called textile waste chains. The repeated use of textile materials can be differentiated in various ways. Reprocessing and primary reuse presuppose that there is no material change. These approaches therefore start after the sorting of post-consumer used textiles. Examples of secondary uses, including reprocessing, are use as cleaning cloths or upcycling into other textile products. The best-known primary use is passing on to the second-hand market [42]. This type is preferable to material recycling according to the waste hierarchy. Furthermore, materials that are too low-grade do not allow for secondary use or resale of the primary type and are therefore currently mostly sent directly to thermal recycling after sorting or to landfill together with the waste and disruptive materials contained in the collection [42-43]. The basis of the recycling of post-consumer used textiles is the material change and can be divided into two categories. Accordingly, these categories start at the recycling stage of the textile recycling process chain as shown in Fig. 2. Open-loop recycling describes secondary recovery as material recycling for the production of nonwovens, insulating materials and other materials [44]. Recycling in the form of open-loops can lead to lower-quality products, which is why such productions are also referred to as downcycling. Most of these products are then currently used in other industries and for other products. As a result, the raw materials contained are lost insofar as they cannot be integrated into the cycle in the form of newly produced clothing articles [43-44]. Closed-loop processes track the reuse of the raw materials and materials for the same type of product. Fibre-to-fibre raw material recycling describes the primary utilisation of post-consumer used textiles and enables the integration of already used raw materials into the new production of textiles, which represents a closed-loop recycling [43].

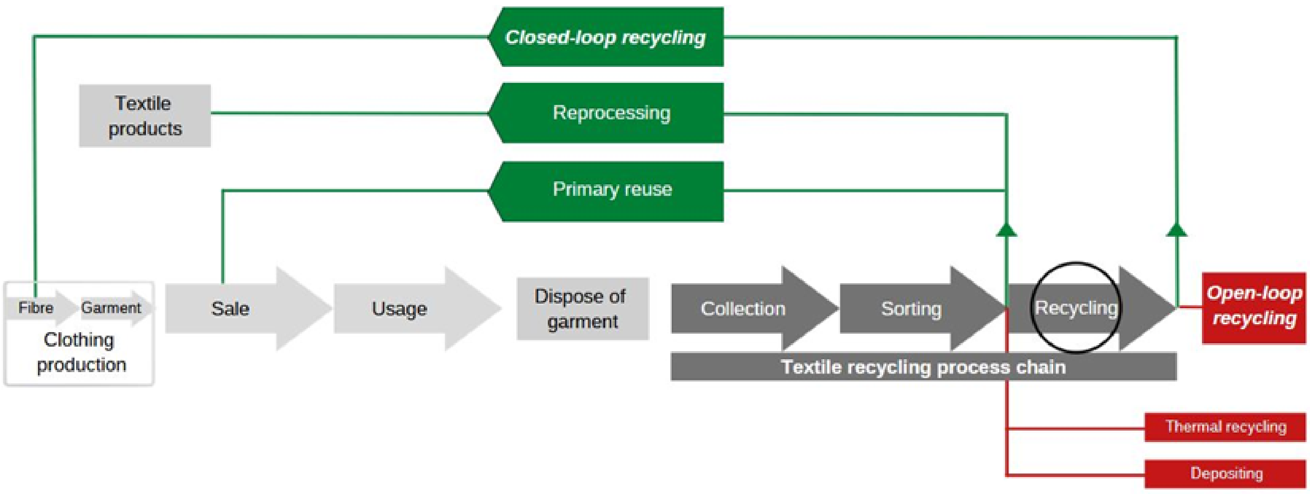

Fig. 2 Closed- and open-loop of textiles.

However, the recycling of discarded textiles is a problem because it is relatively difficult to determine the exact composition of the textile fibers. Therefore, most of it is simply burned or shipped to developing countries and only a very small part is used to produce new articles. Most of the textile waste is recycled chemically by pyrolysis, hydrolysis, hydrothermal recycling etc., or mechanically by shredding [45-46].

A basic distinction is made between textiles' mechanical and chemical recycling [47-48]. For mechanical recycling, the clothing is first sorted according to color and material. The material is then shredded and shortened with the aid of mechanical force. The extraction of secondary fiber material is the basis for further processing of the subsequently torn fibers. However, the force effect reduces the fiber length and thus the quality of the fibers [49]. During chemical recycling, in turn, the material is broken down into its chemical starting materials [50]. This includes the following processes: The solvent-based extraction serves to dissolve the plastic and the associated extraction of the starting polymer. In addition, depolymerization takes place, in which heat is used to break the bond between the different polymers, which results in pure monomer blocks that form the polymers. Finally, raw material recycling takes place. The plastic waste is heated by the application of oxygen (optionally without oxygen) and forms new carbon water chains by recycling the different molecules [51]. However, chemical recycling as a result of various regeneration processes is currently not fundamentally feasible for blended fibers consisting of natural and synthetic fibers. In addition to mechanical and chemical recycling, there is increasing interest in organic recycling of bio-based textile waste, which represents an alternative raw material for the manufacturing of bio-based products. By means of bioconversion, the cellulose content is extracted from the textiles. Also in the case of organic recycling, the effective sorting of textiles according to fibers and colors is a challenge [52]. In order to upgrade the textile product and prepare it for the recycling process, it is essential to recognize its fiber composition so that an effective sorting process can be ensured [53-54]. However, the accuracy and completeness of garment information on label is largely done manually and is very tedious. Therefore, labelling is time-consuming and the information is not always presented correctly [55]. Different methods, such as microscopy, differential scanning calorimetry and gas chromatography, can be used to identify the fiber composition, but these methods are time-consuming and expensive [56-57]. Therefore, attempts are being made to develop automated detection and sorting methods of textile materials, as manual sorting of textile waste is relatively slow and ineffective [58-59]. This is where fiber tagging can help address these challenges and steer textile recycling in the appropriate sustainable direction.

3.2 Methods of identifying the composition of textile waste

Some developments in the field of identification of fibers in textile material recycling have already been presented in a number of studies. Zhou et al. developed automatic textile fiber identification using near-infrared (NIR) spectroscopy and pattern recognition [60-61]. Near-infrared technologies (NIR) are particularly important, as they can be used to non-destructively determine and analyze organic substances [62-63]. While marker systems are unique and counterfeit-proof, questions arise regarding their durability and the complexity of integrating them into existing garment production. In contrast, NIR spectroscopy can be applied to all garments and does not require prior markings. Riba et al. analyzed the textile samples using infrared spectra and statistical multivariate methods that allowed nearly 100% classification accuracy of unknown fiber samples at high speed [64]. Moreover, sorting with the help of radio frequency identification (RFID) and bar codes, which enables automatic and contact-free identification, is also very promising [65-67]. Another field of research covers material preparation about the removal of impurities such as buttons and applications as well as the decolorization of textiles for subsequent processes [68]. Furthermore, research is concerned with various recycling processes about the material type of the textiles. The holistic approach is also targeted in research projects and considers the entire value-added source from the collection of used textiles to their return to the textile raw material to close the loop [69]. The objective is to address consumers and influence their behavior recyclable material sources of materials for a recycling approach of all the aforementioned research fields amount to textile recyclable material sources. These include used garment, defined as waste, and fabric offcuts, defined as production waste. Non-textile recyclable material sources – such as Polyethylenterephthalat (PET) bottles from which polyester fibers can be produced at the end of their life cycle [70] – are not considered within this section.

4 Discussions and future outlook

There is definitely potential for incorporating those textile marking processes into existing or future recycling technologies. It is emphatically noted at this point that evidence is an essential pillar within the circular economy. In this context, it was highlighted that companies could, for example, use it to provide evidence of real recycling rates. Based on the previously described fields of research about detection technologies for material recycling, the question was raised whether the DNA marking process would theoretically also be suitable for this part of the circular economy. This idea is to use textile marking technologies for upstream sorting. Comparatively faster identification by the DNA marker could replace NIR or RFID technologies in this context. The chance of success of this possible innovation is at this point rather low, especially due to the necessary real-time acquisition of data, which is not practically feasible according to the current state of this technology. In addition, it should be emphasized that there are potential advantages compared to non-technical approaches, as well as to the manual sorting currently carried out. If the technological approaches discussed are targeted, e.g. for upstream use in recycling processes, previously unexploited potential can lead to a qualitative increase in textile recyclates. For this purpose, it is necessary to align marking technologies with the information required for recycling. For example, the differentiated material compositions, finishing components and non-textile applications of recyclers within the recycling process should be recognizable and retrievable by appropriate technologies. The efficiency of a marker system heavily depends on its widespread adoption. Large-scale application is questionable if only a few garments are marked. Therefore, such systems might achieve higher efficiency in closed environments, like the leasing of workwear etc. While marker systems can potentially enhance traceability and sustainability, their application in a large-scale recycling context remains challenging. The future of these technologies might be more promising in specialized, closed-loop systems.

Ideally, customers should not only pay attention to the labels and headlines printed on advertisements or product packaging, but also read the back of the packaging, where all ingredients are listed in detail. In addition, it would be beneficial if end users researched the product and the company to get to know it better and to learn where and under what conditions the products are manufactured and what the philosophy behind the brand is. After all of this research has been done, it may be easier to decide if the environmental claims on the products and advertising are true or if the company has used greenwashing to make its products look more environmentally friendly than they are. However, it is not easy, of course, to obtain information about environmental protection strategies, sustainable supply chains and suppliers etc., as companies are not obliged to make this information public.

Nevertheless, those processes are in the early stages of development and no one knows where their path will lead in the future. The whole principle of textile labelling and the ability to identify textiles over a potentially long period of time could be a very interesting approach for the future of textiles. End consumers are realizing that they need to consume more consciously and sustainably, and therefore the question of how these principles can be implemented in everyday life is becoming increasingly relevant for many. Of course, not every aspect of daily routine can be immediately transformed into a more sustainable lifestyle and consumption, but especially in a time of rethinking and rediscovering different sustainable alternatives to produce and recycle textiles in an environmentally friendly way, methods like textile DNA markers could be a solution to facilitate the reuse of textiles and make the transition to a circular economy. In addition, potential negative aspects must be included in the consideration. The question arises as to what social and ecological disadvantages the presented technologies for marking textiles entail. For example, there may be increased consumption of chemicals and rare earths for textile marking, as well as possibly increased energy consumption for the operation of the blockchain approach. Are these textile markers sustainable or is there a risk of environmental impact? These aspects should be mentioned and examined in the further analysis in this context. The question should also be asked to what extent, in such a scenario, small local companies producing raw fibers, for example, can be expected to improve their processes to such an extent that a marking technology can be used or whether this is not profitable due to the high investments involved.

Furthermore, based on the results of the latest studies in the field of perspectives for the textile industry, approaches can be identified that go hand in hand with the previous considerations of this review. According to studies, a worldwide increase in the consideration of sustainability issues in all industrial sectors is postulated for the next few years. The textile industry outlines the increase in prices for emitted carbon dioxide due to the resulting increase in the price of fossil raw materials and these are needed for the production of synthetic fibers. Increasing consumer awareness of environmentally friendly manufacturing and a corresponding recycling process of products is growing and should ideally establish itself as a standard. Politically, it is necessary to further develop resource-saving production and to enshrine this in law [73-74]. Furthermore, the separate collection of textiles from 2025 due to the amendment of the European Parliament’s Directive (EU) 2018/851 is emphasized [75]. Moreover, significant barriers in textile recycling include unclear regulations, the low value of recyclable textiles due to non-existing high-grade recycling opportunities, and insufficient domestic recycling capacity, which is a deterrent for collection efforts [76]. Accordingly, the pressure on both textile manufacturers and retailers to bring recyclable products to the market will increase. At the same time, it is necessary that the new functionalities of textiles with regard to their recyclability and biodegradability should continue to be developed, and that at the same time research into easily recyclable fibers is invested in. From the experts’ point of view, the design-driven approach will soon be taken into account in manufacturing, thus positively influencing the production chain and the life cycle of textile products.

5 Conclusion

The focus of this review was on developments in marking methods to identify textile materials. In summary, almost all the methods presented can contribute to some extent to counteracting greenwashing in textile production and facilitating recycling. Some labelling methods were designed with this aim in mind from the outset, while others were originally developed for a different purpose but still have the potential to be used for textile identification purposes. Practical application of this technology in textile recycling processes would be desirable. As shown in this review, there is still a need for development in this area of application, but on the basis of the data currently available, some potential can be foreseen.

Author Contributions

Sabrina Mauter: conceptualization, methodology, writing – original draft preparation, writing – review and editing, visualization; Victoria Kern: original draft preparation; Lisa Hinz: original draft preparation; Neele Ucke: original draft preparation; Lilia Sabantina: conceptualization, methodology, validation, writing – original draft preparation, writing – review and editing, visualization, supervision, project administration. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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