

Article

Material Textile Design as a Trigger for Transdisciplinary Collaboration: Coating Bio-Based Textiles Using Waste from the Wood Industry

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Abstract: Waste production is a worldwide concern due to its adverse impact on the environment, as well as on the health of living beings. Sustainable development states the urgent need to implement actions to gradually replace fossil resources, including the use of renewable raw materials such as residues and secondary raw materials from other industries as a promising alternative to replace fossil resources. This research explores an approach focused on the design of renewable materials by developing a bio-based textile coating with the use of sawdust from radiata pine, which is the result of industrial wood transformation processes. The methodology adopted a transdisciplinary approach, integrating knowledge from design, engineering, and sociology disciplines. A perceived sawdust quality study was carried out in its original format, while two different coated textile substrates were developed, using knife-over-roller and spray coating processes, which were evaluated from user acceptance and functional performance points of views. Finally, a clothing prototype for workwear, using the bio-based coatings, was developed, employing a mono-material design concept (i.e., using the same material in all its forms). The results obtained from users and laboratory studies favour the knife-over-roller coating and the removable clothing design, which provides improved usability performance. The obtained conclusions highlight that transdisciplinary collaboration is essential to address complex challenges in the development of solutions, placing the design of material as a necessary prior action in the design process of final products.

Keywords: bio-based materials; sawdust; mono-material design; transdisciplinary collaboration



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1. Introduction

1.1. Circular Focus

Waste production is a global concern due to its adverse effects on both the environment and the health of human beings [1].

From the decade of the 2000s, on a global scale, the circular economy has become a core issue in many political, industrial, and academic discourses, with initiatives aimed at rethinking the traditional economic models towards circular and sustainable systems, to reduce wastes, reuse materials and look for more environmentally responsible production processes [2,3]. According to the Ellen MacArthur Foundation [4], the circular economy is

an industrial system which is intentionally structured to be restorative and regenerative. It replaces the traditional end-of-life concept by emphasizing the elimination of toxic chemicals that affect reuse and prioritizing waste reduction through the optimized design of materials, products, and systems. Several studies have focused on consumers and industry awareness in environmental responsibility [5,6]. There is a growing tendency, among consumers to extend life of products, which is motivated both by the repairability of products and by increased environmental awareness [7–9], showing a change in behaviour which gives value to products that respond to functional, emotional and environmental factors [10–12]. This evolution focus, as well as the imminent need to reduce the polluting process at every level, has an impact on the manufacturers' decisions regarding what and how to produce [13,14]. Sustainable development raises the urgent need to implement actions to gradually dispense with the use of fossil resources. From this perspective, the bioeconomy emerges as an alternative that provides bio-based materials to find new solutions for reducing dependence on non-renewable sources and reducing environmental impact [15,16].

1.2. Agro-Industrial Wastes and Bio-Based Textile Materials

The use of waste as a raw material to manufacture products has generated new ways to contribute to environmental sustainability. Bio-based materials are those derived from biomass [17] of renewable origin which are characterized as more biodegradable and generate a lower carbon footprint compared to traditional materials [18,19]. Currently, 2010 million tons of agro-industrial waste are produced worldwide, and this is estimated to increase to 3400 million tons by 2050 [20]. The use of agro-industrial waste is creating great interest in the textile industry, as result of the growing demand for environmentally friendly materials [21]. This type of residues represents a significant opportunity to improve sustainability in the textile industry, innovate in materials, and respond to a growing demand for products which prevent environmental damage [22,23]. They could become alternatives to replace highly polluting materials, which are obtained from fossil-based sources, for several industrial sectors [24]. This use would allow converting waste into valuable resources and favour the innovation of a sustainable approach which attracts an increasingly environmentally conscious market [25,26]. The textile industry could reduce its dependence on conventional raw materials, such as cotton and polyester, which have a high environmental impact in terms of water use, land use, and emissions. Sawdust is a global agro-industrial residue obtained from wood processing and exploitation activities. Its storage under uncontrolled conditions can result in environmental problems derived from toxic chemicals and greenhouse emissions, as well as the generation of leachates that affect surrounding groundwater and surface water sources [27]. Sawdust possesses valuable properties such as good mechanical stability, rough surface, high porosity, high surface area, absorbency, high carbon content, easy biodegradation, and easy modification, which allows its application in different areas, such as in the case of bio-based textile materials [28–31].

1.3. Transdisciplinary Collaboration and Mono-Material Design

In the European Union, consumers produce about 5.8 million tons of textile waste each year, of which 25% is recycled and 75% is landfilled or incinerated [32,33]. Although this industry has a great impact on the economy, generating USD 2.5 trillion annually [34], the overuse of water, polluting materials, chemicals, etc., has a significant socio-environmental impact. Mitigating the permanent damage generated is consistent with contributions that come from a transdisciplinary approach. The integration of various disciplines allows addressing problems from multiple perspectives, favouring the identification of opportunities

to design new solutions for the textile industry and revealing the revaluation of industrial waste as a possible alternative.

This study highlights how textile materials' design can act as a trigger for transdisciplinary collaboration, underlining the importance of integrating knowledge from various disciplines to holistically address challenges which are inherent to bio-based materials research. When it comes to projecting a bio-based material, the process of research and the definition of answers is more complex [35], as it involves considering additional variables, such as waste use and treatment, carbon footprint minimization, and a controlled life cycle [36], aspects which are perfectly aligned with circular economy principles [37–39]. The assessment of perceived quality and user acceptance is crucial to developing comprehensive and systemic solutions [40–42]. In this scenario, design, technical innovation, user acceptance, and market prospection are required, which are favoured in transdisciplinary research.

From a sustainable approach, the mono-material design is presented as a key strategy to address some of the most critical challenges in waste management. Mono-material design simplifies the recycling process by using a single type of material in product manufacturing [43]. This avoids the need to separate different materials at the end of their life cycle, reducing costs and improving recycling efficiency. By eliminating the barriers presented by products made of composite or mixed materials, the recyclability rate is significantly increased. In addition, the design of mono-material products reduces cross-contamination during recycling that, in turn, reduces non-recyclable waste generation. This approach contributes to reducing the environmental footprint of products, aligning with global sustainability goals [44,45].

The development and production of materials have undergone significant evolution, increasingly embracing innovative methodologies and paradigms that prioritize novel approaches to material design. This shift reflects a growing emphasis on transdisciplinary collaboration, which has become essential for addressing complex challenges that cannot be resolved within the confines of individual disciplines [46–49]. This complexity is particularly pronounced in the domain of bio-based materials design [50], where the number of variables and interdependencies significantly increases. As a result, research in this area necessitates and fosters even closer transdisciplinary collaboration, facilitating the development of holistic frameworks that integrate diverse knowledge domains to achieve viable, sustainable solutions [51]. Such an integrative perspective, as opposed to an additive one, emerges when researchers transcend disciplinary boundaries—both theoretical and methodological—to co-create a unified conceptual framework [52]. This convergence of knowledge not only bridges academic disciplines but also brings together stakeholders from the public and private sectors, creating a dynamic platform for innovation and addressing contemporary challenges [53].

1.4. Methodological Focus

The methodology applied in this research considers a transdisciplinary approach, integrating knowledge and experiences from the disciplines of industrial design, textile design, transdisciplinary design, chemical engineering, wood industry engineering, and sociology. This transdisciplinary approach allows addressing complex problems in a holistic way to generate coherent solutions to reuse waste from MASISA S.A, the main wood panels company in Chile, whose processes generate about 300 tons of sawdust per month, revaluing only 28% of these. The research was focused on the development of textile coatings by using radiata pine sawdust. The materials used in the coatings, as well as in textile substrates, are all renewable in order to obtain a sustainable material approach [54]. The concept of mono-material design is explored to improve the mechanical recycling

potential of items of clothing at the end of their life cycle [55]. Mechanical recycling prototypes were manufactured at CITEVE (Technological Center of Textile and Clothing Industry in Portugal). Studies of sawdust's perceived quality were carried out in an original format provided by the company, and coatings were implemented under quantitative, descriptive correlational, cross-sectional, and non-experimental methodological approach.

2. Materials and Methods

2.1. Transdisciplinary Approach

The disciplines involved in the current research are industrial design, textile design, transdisciplinary design, chemical engineering, wood industry engineering, and sociology, coming from organizations in Europe and Latin America. The main concept is the development of a mono-material solution for clothing for craft work, manufactured with bio-based materials including a Lyocell textile structure made from cellulosic wood and a coating made with radiata pine sawdust, a wood industry waste. Mono-material favours mechanical recycling at the end of the product use cycle, which favours a circular economy approach. The chemical engineering industry oversees waste characterization and its technical treatment, assessing formulas for coating mixtures, the definition of the application of coating techniques, and the selection of textile substrates, consistent with sustainable approaches. Engineering performs testing of material prototypes in wood industries in the laboratory and interprets the technical data. The industrial design area involves crossed and collaborative participation in every action carried out. It leads on the perceptual characterization of residues, and conducts material and clothing prototyping experiments, together with chemical engineers and textile designers. It collaborates in the elaboration of instruments to gather perceptual information related to sawdust and the prototypes of the two materials developed. It validates the clothing process and is endorsed by experts and users. Sociology specialists make adjustments to perceptual information, gathering instruments and interpreting the data collected, evaluating the user acceptance level. When dealing with materials that integrate waste in their composition, prospecting user acceptance is especially important. A transdisciplinary design approach provides a structure focused on the collaboration and inter-relation of disciplines involved in research. It helps to see the problem as an opportunity to think of a systemic solution that revalues the sawdust generated by the wood industry and jumpstarts an impulse throughout the organization of the disciplines, institutions, and their roles (Figure 1).

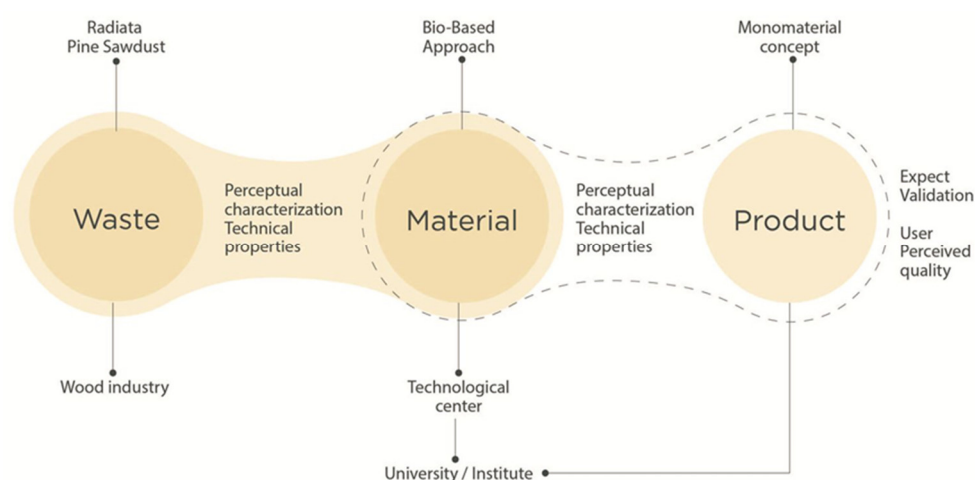


Figure 1. Transdisciplinary approach process with stakeholders and waste pathing.

2.2. Phases of the Transdisciplinary Process

The research process is structured in three main phases, consisting of co-design, co-production, and reintegration [56,57]. In the co-design phase, common objectives are defined, and the problem is jointly conceptualized among research participants coming from academia, the industry, and the technology centre. This phase is crucial to develop a shared understanding of problem and to ensure that the disciplines and entities are aligned with the project challenge. During the co-production phase, collaborative knowledge generation that integrates scientific knowledge with technical knowledge is emphasized. Iterative processes are developed to continuously improve the concept, design, and experimentation through material and clothing prototypes. The reintegration phase allows proposing a strategy that makes the co-created knowledge visible. In this research, the relationship between the stakeholders involved, as well as the transfer system for the integration of the product into the market, consists of the generation of synergies between public and private entities. MASISA S.A., the primary supplier of residues, seeks to strengthen its corporate social responsibility, committing itself to the preservation of the environment and adopting practices focused on sustainability and the circular economy. Education and research entities are articulating agents to allow the knowledge generated to be transferred to various actors of territorial system.

2.3. Exploratory Design Phases

2.3.1. Exploration of Coating

The sawdust provided by MASISA S.A. was processed through a dehydration process at 40 °C for 72 h to eliminate residual moisture. Subsequently, it was introduced into an electric sieve until it reached a particle size of 200 microns. The textile substrate used was a Lyocell knitted fabric (a circular knitted jersey structure, with 300 g/sqm), with Lyocell being a fibre produced from wood pulp that is derived from sustainable grown trees, possessing the advantage that it does not require the use of environmentally harmful chemicals. A knitted substrate was chosen due to its higher stretchability compared with weaved fabrics, and therefore increased comfort was expected for users.

The coating was composed of a bio-based polymer blend with 89.7% bio-based polyurethane polymer (Tubicoat from CHT, Tübingen, Germany), 10% sawdust and 0.3% a water-based crosslinker (Imprafix from Covestro, Leverkusen, Germany), homogenized with a mechanical stirrer (Figure 2). The formulation was optimized for this residue, and it was used as it is for the knife-on-roller coating and diluted twice in water for the spray-coating process. The study focused on studying the application techniques, since different appearances and properties were aimed at for the clothing prototype.

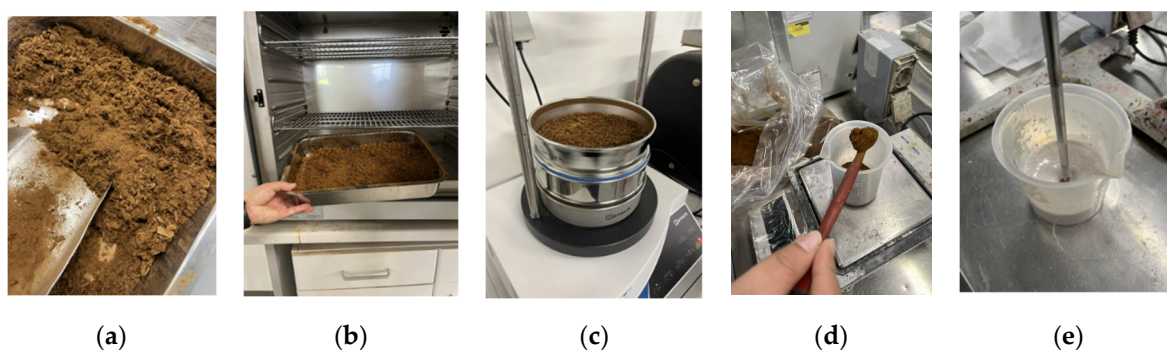


Figure 2. (a) Sawdust put on tray to enter the drying oven, (b) sawdust in drying oven, (c) sawdust in Retsch AS 200 CONTROL (Retsch, Haan, Germany) analytical sieve shaker, (d) sawdust weighed in Mettler Toledo PG5002-S Delta Range (Mettler Toledo, Columbus, OH, USA), (e) homogenization of the coating mixture in a mechanical agitator, Techmatic S2 (Techmatic, Detroit, MI, USA).

As such, two types of coatings were performed on the textile substrate. Coating 1 was performed by spraying with a compressed air gun (Graco Inc., Minneapolis, MN, USA), adding 50% of the water to make it compatible with the equipment used. Once coated, the textile fabric was introduced into a hot air tunnel (ROQ, Oliveira Santa Maria, Portugal) at 100 °C and 5 m/min to evaporate the water and reach the optimum drying conditions. Coating 2 was carried out by means of a knife-on-roller process in Mathis AG LABCOATER type “LTE-S” (Werner Mathis AG, Oberhasli, Switzerland) multifunctional equipment, with a thickness of 1 millimetre. Subsequently, it was subjected to a thermosetting process at 100 °C and 5 m/min to improve the adhesion of the coating to the textile substrate. A topcoat was applied using an opaque bio-based polyurethane with transparency and flexibility (Lamberti, Gallarate, Italy) to improve the mechanical properties of the material. The entire process was carried out at a temperature of 100 °C and 5 m/min (Figure 3). The coating add-on weight was lower than 3% and 18%, respectively, considering Coating 1 and Coating 2, on the final mass.

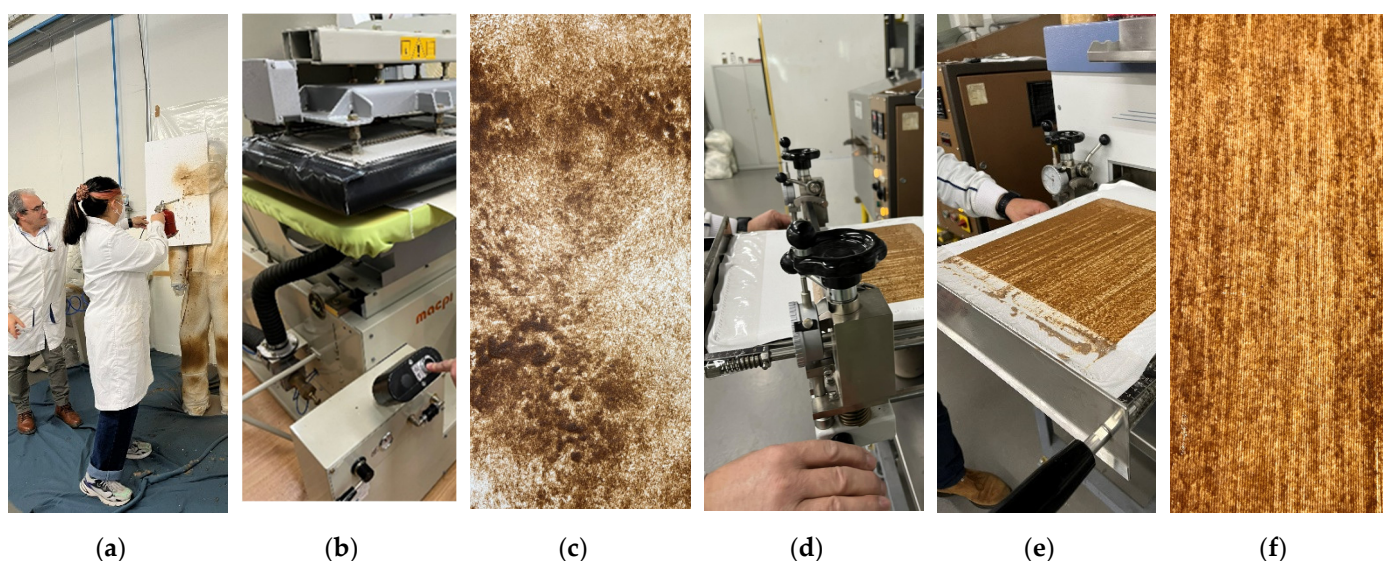


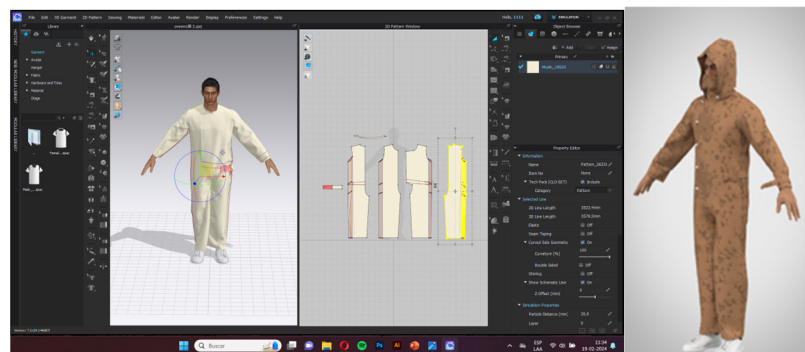
Figure 3. (a) Application of the coating mixture by spraying it with a compressed air gun, (b) pressing in industrial flat bonding press, Macpi 553.37-9124 (Macpi, Brescia, Italy), applying pressure and heat, (c) visual aspect of Coating 1, (d) and the (e) application of the mixture with the knife-on-roller technique in Mathis AG LABCOATER type “LTE-S” (Werner Mathis AG, Oberhasli, Switzerland) equipment, (f) visual aspect coating 2.

2.3.2. Applied Exploration of Materials

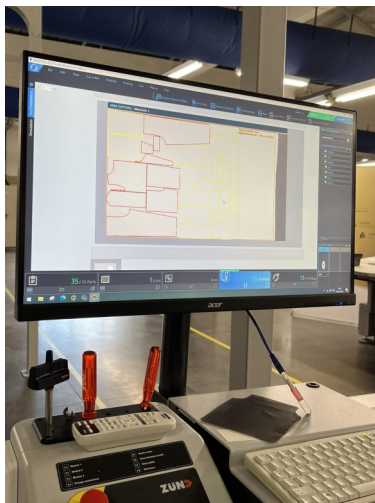
The clothing design is aimed at users who carry out craft work, such as painters and ceramicists, among others. The conceptual idea considered a mono-material approach; that is, that the garment solves every function with the designed material to favour mechanical recycling at the end of its life cycle. Three clothing models were designed by using CLO 3D software (2024.1, CLO Virtual Fashion Inc., Seoul, Republic of Korea), which allows for modelling in three dimensions and generating two-dimensional patterns simultaneously. Patterns were rectified and processed on a Zünd G3 cutter (Zünd, Altstätten, Switzerland). The sewing was performed using straight machines and industrial overlock (Figure 4).

The first prototype was a mono-material coverall that incorporated a head-and-face protection cup. A fitted system for the lumbers, waist, and fist was incorporated in order to provide a better coverall fitting for users. The second prototype incorporated a removable head-and-face protection cup, as well as adaptable gussets to support mobility. The third prototype was a two-piece coverall, where reinforced stitching was incorporated for better durability and resistance. Buttons and adjustment systems were manufactured with the

same textile material and fibres ground in a Retsch SM 300 (Retsch, Haan, Germany) cutting mill machine (Figure 5).



(a)



(b)



(c)



(d)

Figure 4. (a) The use of CLO 3D software for 3D modelling and 2D pattern making, (b) pattern/fabric optimization in CLO 3D software (2024.1), (c) Zünd G3 fabric cutting table, (d) Pfaff 1183 industrial straight sewing machine (Pfaff Industriesysteme, Kaiserslautern, Germany).



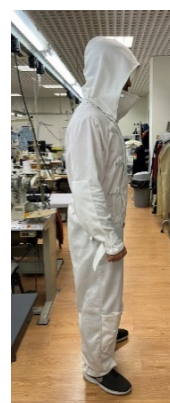
(a)



(b)



(c)



(d)



(e)



(f)

Figure 5. Cont.

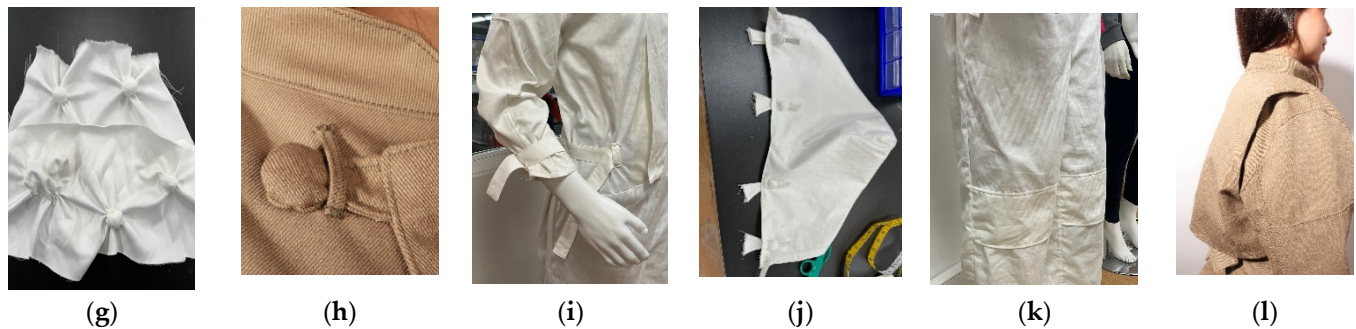


Figure 5. (a) Prototype 1, front view, (b) Prototype 1, side view, (c) Prototype 2, front view, (d) Prototype 2, side view, (e) Prototype 3, side view, (f) Prototype 3, front view, (g) mono-material stuffing experiment, (h) mono-material button experiment, (i) adjustment straps, (j) front buttons, (k) reinforcement seams, (l) adaptable gussets.

2.3.3. Perceived Quality Studies

Sawdust Study Method

In a first approach, the sawdust supplied by MASISA S.A. was evaluated by end-users to understand its natural properties and influence on the potential applications in products used daily by users. The methodological approach adopted was quantitative, descriptive correlational, cross-sectional, and non-experimental in nature. A non-probabilistic purposive sample in a controlled environment was considered, selecting 85 participants in a controlled environment. The sample was non-probabilistic and used purposive convenience sampling. A self-administered questionnaire was implemented with semantic differential tables and quantifiable options for data collection, using a Likert-type response scale. The dimensions assessed included visual, olfactory, tactile, instrumental, associative, and emotional aspects. The scale was based on an axis that represented one attribute, while the other axis indicated the opposite attribute, on a 1 to 5 scale, with the value 3 as the neutral point. Cronbach's alpha was used to assess the reliability, which measured the internal consistency correlating with the means of every item. The test gave a value of 0.69 and the inter-item correlation average was within the range established by Clark and Watson (1995) [58]; therefore, the internal consistency of the instrument was considered acceptable. To systematize the superficial, associative, and emotional perceptions, the database was downloaded in a MS Office[®] Excel sheet, so the data were cleaned, transformed, and processed in RStudio[®] interface version 2024.04.02 (Posit Software, Boston, MA, USA), using R programming language version 4.1.1. Correlational analysis of the materials presented perception, potential usefulness descriptions, and relevant characteristics for purchase, which were carried out. Spearman's correlation, which is appropriate for common variables and non-parametric data, was used to analyze relationships between the variables [59].

Coating Study Method

The coated samples were also subjected to a perceived quality study by 32 users. A statistical analysis of perceptions was carried out to understand the individual samples with respect to the two options of coatings developed. In order to systematize visual, olfactory, tactile, instrumental, associative, and emotional perceptions, the database was downloaded into a MS Office[®] Excel spreadsheet, and then the data were cleaned, transformed, and processed in RStudio[®] interface version 2024.04.02, by using the R programming language version 4.1.1. To measure perceptions, semantic differential scales were used, where one axis represents one attribute, while the other axis points to the opposite attribute, on a 1 to 5 scale, with the value 3 as the neutral point. Correlational analysis of the perception of the materials presented and their potential uses as coatings was carried out, as well as the description of their potential usefulness and relevant characteristics for purchase.

These analyses made it possible to establish relationships between participants' survey perceptions and the commercial viability of the analyzed coatings. The internal consistency of the items was measured by Cronbach's alpha, which yielded an index of 0.67, with a 95% confidence value of 0.41 at the lower limit and 0.85 at the upper limit being within range of acceptability.

Clothing Validation by Users

Finally, the physical and psychological comfort validation of clothing prototypes was also carried out with 10 potential users, subjecting a high-fidelity prototype of craft work clothing to functional testing. The validation process lasts for eight working hours, with users making a physical and audiovisual record during one working day in a pottery workshop. At the end of the day, a structured interview was carried out, through the application of qualitative questionnaire and open questions. The results were processed using RStudio[®] software version 2024.04.02 and qualitative evaluation.

Material Tearing Strength Testing

The developed material samples were tested for their mechanical properties according to the ASTM D 5587 Standard Test Method for the Tearing Strength of Fabrics by the Trapezoid Procedure. For this test, five specimens taken from the machine direction to measure moisture equilibrium in the standard atmosphere were considered. The sample format was rectangular, with 75mm width and 150 mm length, and an outline of an isosceles trapezoid was marked on the specimen. The specimen was slit at the centre of the smallest base of the trapezoid to start the tear. The test was carried out at the speed of 300 ± 10 mm (12 ± 0.5 in./min) in the Instron 4468 machine.

Water Vapour Transmission Rate

The samples were tested for their thermal insulation and breathability properties by determining their water vapour transmission rate, according to the standard ASTM E96/E96M [60], using the Desiccant Method. The sample test specimens (in triplicate), which were 70 mm in diameter, were placed in a test dish of 200 cm³ containing 20 g of desiccant. The test dish was then sealed and incubated in a climate chamber at 23°C and 50% (± 3) relative humidity. The weight variation was controlled with a precision of 0.01 g at regular intervals every 24 h. The weight variation represents the amount of water vapour that was transferred from the environment to the desiccant. The weight was then plotted against the time, and a regression curve was taken to enable the calculation of the water vapour transmission, using the following equation:

$$WVT = \frac{G}{tA} = \frac{\left(\frac{G}{t}\right)}{A} \quad (1)$$

where

WVT = rate of water vapor transmission, g/h.m²

G = weight change (from the straight line), in g

t = time, in h

G/t = slope of the straight line, in g/h

A = test area (cup mouth area), in m²

Determination of Volatile Loss

To evaluate the emission of volatile organic compounds (VOC) from the selected textile materials, the methodology described in ASTM D1203–94 [61] was employed. The test samples were placed in direct contact with activated carbon, which captured the volatile

compounds emitted by the material during the test. A 500 cm³ container was used to place the sample and the activated carbon distributed in 120 cm³ layers, which were heated in an oven at 70°C for a period of 24 h. The samples were then removed, left at room temperature for 24 h, and then weighed again to calculate the weight loss due to the volatilization of the organic compounds present. The weight loss of VOCs was calculated according to Equation (2):

$$\text{Weight loss, \%} = \frac{[W_1 - W_2]}{W_1} * 100 \quad (2)$$

where

W_1 = initial weight of test specimen, and

W_2 = final weight of test specimen.

3. Results

3.1. Sawdust Validation by Users

The sawdust used in this work was subjected to a perceived quality study by 85 participants, as described in the previous section. Regarding gender distribution, most of the respondents identified themselves as female (55.29%), followed by those who identified themselves as male (40%). Only one person (1.18%) did not identify with any gender, and three (3.53%) preferred not to respond. With respect to age, a marked difference was observed, where 97.65% of participants were in the 18 to 28 age range and 2.35% were in the 29 to 41 age range.

Regarding occupation, 80% of participants were undergraduate design students, 12.94% design academics, 2.35% unemployed people, and 4.71% are in other situations, such as informal jobs unrelated to design.

In the sawdust perceptual study, sensory dimensions were evaluated and gave significant results in terms of visual, olfactory, tactile, instrumental, associative, and emotional perceptions. For visual dimension, sawdust was predominantly perceived as having a matte finish, with 50% frequency and a perception index of 0.49. It was considered mostly opaque, with 48.2% of responses indicating a high level of opacity and a perception index of 0.15 for medium and low opacity levels. The texture of the material was a relevant characteristic, with over 80% total frequency, and there was an evenly distribution among textures, resulting in a perception index of 10. In terms of olfactory analysis, despite the fact that many participants could not identify or were indifferent to this characteristic, some indices indicated the existence of trends. Sawdust was perceived as pleasant (index of 2.06), natural (3.71), relaxing (1.50), defined (1.09), and soft (1.33). In the tactile dimension, results showed it as warm, with an index of 1.48, and ductile, with an index of 1.62. In case of the instrumental dimension, participants evaluated sawdust as versatile (index of 6.50), durable (3.00), and adaptable (1.00), showing that the material has diverse practical applications with potential acceptance by users. In the associative dimension, sawdust was related to characteristics of naturalness, with an index of 2.43 and a frequency of 31.8% in the extreme values of the naturalness axis. It was also perceived as familiar, with index of 2.10, indicating a connection with previous or known experiences. The emotional dimension showed a notable neutral response, except from the comfortable/uncomfortable axis. However, sawdust was perceived as welcoming (index of 2.14), attractive (2.05), comfortable (2.17), and calm (2.32). The other emotional aspects highlighted were confidence (1.31), cheerfulness (1.35), and comfort (1.95) (Table 1).

Table 1. Summary of sawdust’s characteristics with the highest perceived repetition in each dimension.

Dimension	Main Characteristics
Visual	Matte, opaque, textured
Olfactory	Natural, relaxing, definite, smooth
Tactile	Warm, ductile, light, soft, rough
Instrumental	Versatile, durable, adaptable
Associative	Natural, familiar
Emotional	Friendly, attractive, calm, confident, cheerful, pleasant, comfortable

The results indicated the positive disposition of respondents towards sawdust, with an acceptance rate of 59.52%. This suggests favourable openness from potential users towards its application in commonly used objects, as well as in living environments. Regarding the type of use, 33.73% indicated it should be used as a non-visible material, and 34.94% indicated that the best option is in coverings for visible surfaces. A total of 59.09% considered that it should be used in functional objects, while 40.91% considered that it is appropriate for decorative objects. A total of 61.36% indicated that it could be used in coatings for frequently used products. A total of 69.88% stated they had seen objects with a similar visual appearance to sawdust; 48.19% had seen coatings similar to sawdust. In general, the olfactory dimension presents a good correlation with emotional preferences, and significantly, its natural odour correlates mostly with the associative dimension, both in natural and familiar axes. Therefore, sawdust presents with positive user acceptance conditions in the studied environment, derived from the analysis of variables submitted for questioning. Its application in coatings and the exploration of non-conventional substrates, such as natural textile fabrics, stands out.

3.2. Coatings Validation by Users

In this work, concerning the development of materials, a Lyocell fabric with coatings 1 and 2 was subjected to a perceived quality study, as described in Section 2. The perceptual study of coatings evaluated sensory dimensions (Figures 6 and 7), which yielded significant results in terms of visual, olfactory, tactile, instrumental, associative, and emotional perceptions. For the visual dimension, the material with coating 1 was mainly perceived as having a matte finish, which was found in 85% of responses, and it was considered non-reflective by 90% of respondents. On the other hand, the material with coating 2 showed an even more accentuated perception of these characteristics, where 95% of respondents described it as matte and non-reflective. Coating 2 was perceived as cold by 55%, and 40% perceived it as warm. Coating 1 was described as light by 50% of respondents, while coating 2 scored 80% in this perception. The material with coating 1 was perceived as strong by 45% of participants, compared to 55% who perceived the material with coating 2 in the same way. The material with coating 2 was also perceived as ductile by 65% of participants. In the instrumental dimension, the material with coating 1 was described as light by 50% of respondents, and the material with coating 2 scored 80% in this perception. In the associative dimension, coating 1 was perceived as simple by 65% of respondents, while coating 2 scored 55% in this perception. In terms of naturalness, 60% of participants considered the material with coating 1 natural, compared to 55% for the material with coating 2. Finally, in the emotional dimension, the material with coating 2 was seen as comfortable by 65%, and in terms of attractiveness, the material with coating 2 was perceived as attractive by 70% of the participants. The perceptual evaluation of these materials yielded significant insights across the assessed dimensions. Both coatings were predominantly identified as matte and non-reflective, with these qualities emphasized in coating 2 to a greater extent. Additionally, coating 2 received higher ratings in attributes such as lightness and ductility, whereas coating 1 stood out for its simplicity and natural

appearance. Coating 2 was mainly associated with comfort and attractiveness, highlighting its superior sensory and esthetic appeal.

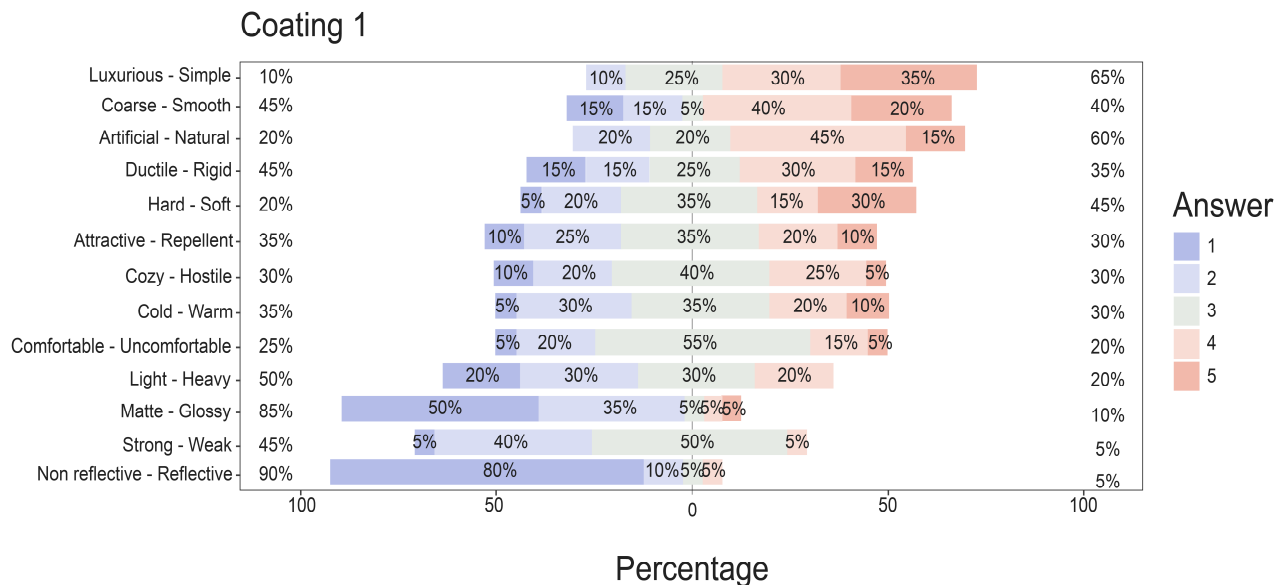


Figure 6. Summary of evaluation of material with coating 1's sensory dimensions.

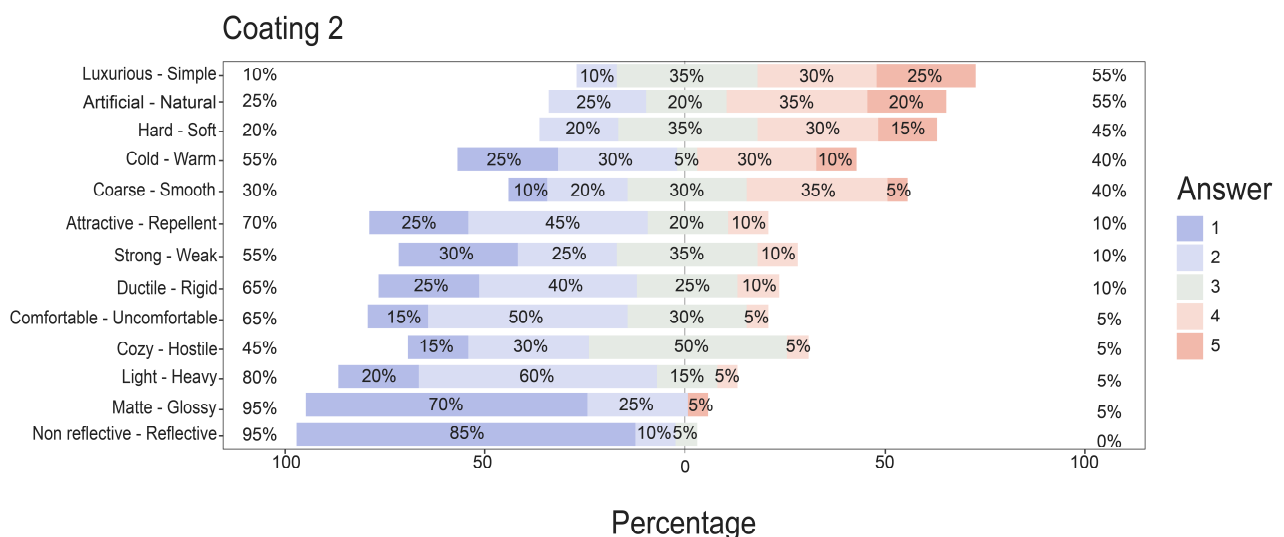


Figure 7. Summary of evaluation of material with coating 2's sensory dimensions.

The Wilcoxon-Mann-Whitney test ($W = 104$, $p = 0.01$, effect = 0.43) determined the coated material 2 to be the one with better acceptance in terms of coating potential, with 100% acceptance. As for the category where the coating would present a better utility, a similar tendency was observed in both samples, where both materials are most associated with use in craft work clothing (40% for coated material 1 and 47.37% for coated material 2), then as casual/urban clothing (30% for coated material 1 and 31.58% for coated material 2), and thirdly as protective or safety clothing (25% for material with coating 1 and 21.05% for material with coating 2), where only coated material 1 was related to sports clothing. From the above results, it can be concluded that, although both materials present similar a hierarchy of associations, craft work clothing had a higher association in coated material 2, as well as in casual/urban clothing, while for the material with coating 1, the use as safe protection clothing was higher than coated material 2. Regarding the reasons for purchase, 30% of respondents would prefer to buy coated material 1 due to its accessibility; 50%

would do so for esthetic reasons; 40% of respondents would value its resistance; 30% would prefer it for its easy maintenance; and 5% would buy for comfort. For the material with coating 2, 65% would choose it for its durability; 45% would choose it for esthetic reasons; and 45% for resistance.

Twenty-five percent of respondents preferred coated material 2 because of its easy maintenance. Overall, coated material 2 demonstrated greater acceptance compared to the material with coating 1. This is evidenced by respondents' inclination towards more favourable perceptions in terms of attractiveness, comfort, and ductility for coated material 2. While preferences in material utility categories were generally similar, with a notable focus on workwear, the material with coating 2 stood out for its accessibility, positioning it as a more highly valued choice among consumers.

3.3. Clothing Validation by Users

The physical and psychological comfort validation of the clothing prototypes was carried out as described in Section 2, with 10 potential users who used the prototype for eight working hours (one working day) in a pottery workshop. After that, the users were interviewed and invited to reply to a qualitative questionnaire. Users positively valued the minimalist and mono-material approach in clothing. The characteristics of the fabric in terms of its technical constitution and perceived quality were well-appreciated. Clothing flexibility was an appreciated factor, indicating that the products allowed them to move easily during tasks on-site. In addition, comfort was highlighted, with the participants mentioning that they always felt safe wearing the clothing. Additionally, in their positive evaluation, they suggested ideas for improvement which could increase the product's functionality, such as integrating additional hooks and pockets for tools. Their feedback will be guidelines for design optimization, aiming at obtaining better practical requirements for users in craft work environments.

3.4. Material Tearing Strength Testing

The developed material samples, i.e., Lyocell control fabric (without coating), Lyocell fabric with a spray-applied coating (Coating 1), and Lyocell fabric with coating and topcoat (Coating 2), were tested for their mechanical properties, as previously described in Section 2. The obtained results are shown in Table 2.

Tensile test results show significant differences with respect to the evaluated materials. The Lyocell control sample (without coating) reached a maximum load of 0.27 kN and a significantly higher extension of 86 mm compared with coated samples.

Coated material 1 showed a higher tensile strength, with a maximum load of 0.53 kN, but the elongation was significantly lower (only around 11 mm), meaning that the comfort properties of the coated fabric, in terms of stretchability, were compromised. Finally, it was seen that coated material 2 showed a slight improvement in tensile strength (around 0.31 kN), but the elongation attained was in a similar range (around 60 mm), meaning that the coating was not interfering with the mechanical properties of the base Lyocell fabric. These results confirm the perception studies with the users in relation to the comfort dimension.

Table 2. Tensile test results.

Test Sample	Material	Load (kN)	Elongation (mm)
Control fabric	Lyocell	0.27	86
Coating 1	Material 1 (Lyocell with spray-applied coating)	0.53	11
Coating 2	Material 2 (Lyocell with coating and topcoat)	0.31	60

3.5. Water Vapour Transmission Rate

To determine the breathability properties of the developed materials, the water vapour transmission rate was determined, according to the standard ASTM E96/96M. [60]

The weight variation was followed for 7 days, being the sample weight registered in function of the time (Figure 8). Regression analysis was performed for each regression curve, and the WVT was calculated (Table 3).

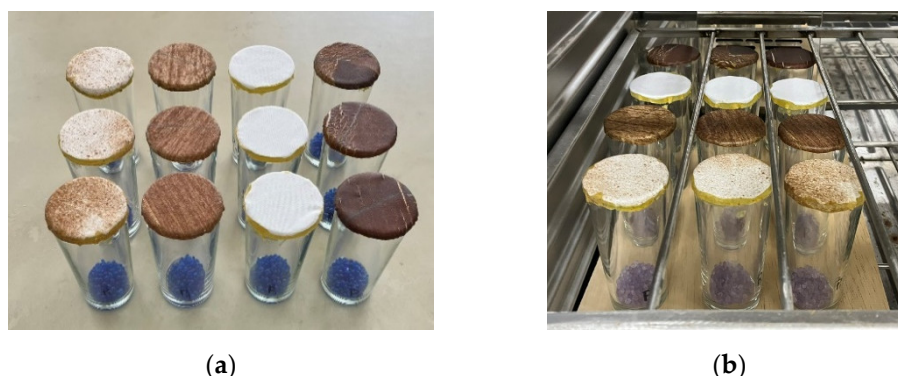


Figure 8. (a) Overview of the samples in the sealed test vessels before water adsorption, (b) overview of the samples in the sealed test vessels after water adsorption and the climate chamber conditions used in the determination of the water vapour transmission rate.

The Lyocell fabric presented a WVT of 1.25 g/h.m^2 . Regarding coated material 1, there was a slight increase in the WVT (1.32 g/h.m^2), that can be explained by the adsorption of humidity by the sawdust. Contrarily, coated material 2 showed a decrease in the WVT, to 0.86 g/h.m^2 , which can be explained by the homogeneous coating at the fabric surface that might block the passage of water vapour through the sample. Water vapour transmission (WVT) and water resistance (WR) are two important properties of functional textiles for thermo-physiological comfort for the human body. WVT maximizes the comfort level of the human body, and the higher the better, since that means that the fabric breathability is increased and water vapour can pass easily through the fabric surface (Figure 9).

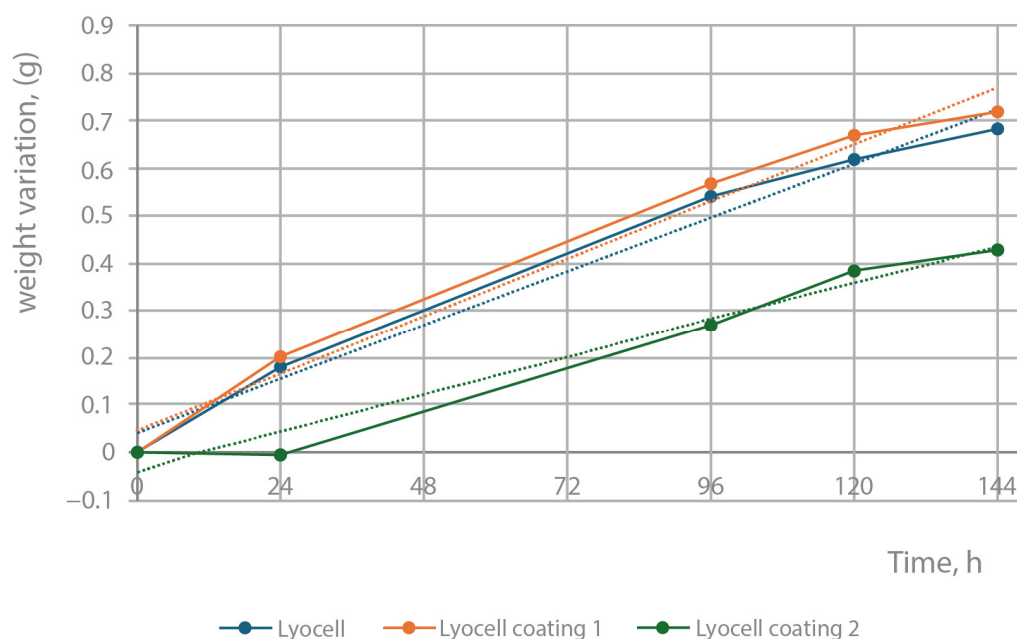


Figure 9. Regression curves for the data obtained for the weight variation in function of the time, for the different tested samples (Lyocell, coated material 1 and coated material 2).

Finally, the emission of volatile compounds from the selected textile materials was also evaluated according to the standard ASTM D1203–94 [61], as described in Section 2 (Figure 10). This test is essential to evaluate the stability of materials and their possible impact on air quality in workspaces, being considered low when the weight loss variation is below 1%.



Figure 10. (a) Visualization of the textile samples in the test vessel containing the activated carbon during the trial, and (b) visualization of the textile samples in the test vessel containing the activated carbon at the end of the trial.

Table 3 shows the results for the weight loss variation due to the emission of VOCs from the samples. As can be seen, only the sample material with coating 1 has a higher emission of VOCs, showing a weight loss variation of 3.6%. This value can be explained by the adsorption and desorption of VOCs from the sawdust, which is sprayed onto the fabric. When the sawdust was encapsulated by a top coating finishing, the emissions were greatly reduced and a value of 1.1% for the weight loss was attained, which was very similar to the control sample. These results are also in agreement with the WVT results.

Table 3. WVT and weight loss results.

Test Sample	Material	WVT (g/h.m ²)	Weight Loss (%)
Control fabric	Lyocell	1.25 ± 0.18	0.8 ± 0.7
Coating 1	Lyocell with spray-applied coating	1.32 ± 0.19	3.6 ± 0.3
Coating 2	Lyocell with coating and topcoat	0.85 ± 0.12	1.1 ± 0.4

The materials' characterization results are in agreement with the results of the perceived quality studies, and they motivated the selection of coated material 2 for manufacturing the craft work clothing prototypes which were built using Lyocell with a coating and topcoat.

The results achieved provide a positive view on the feasibility of coating textiles with blends including sawdust. Exploring the use of these residues in the field of clothing could provide an opportunity for MASISA S.A. and other similar companies to find a solution to revaluing higher percentage of wastes. To realize this, a complete management system is necessary to allow the entire logistics and value chain to work together in one territory, so as to ensure the waste transfer, treatment, and processing cycle to be carried out properly. Additional actions could be developed to solve the systemic and logistical aspects [62].

This research experience proves that transdisciplinary collaboration power is a fundamental part of generating positive and empathetic synergies between the actors and agents involved in the search for innovative solutions that benefit both industry and the environment. Future research could focus on developing this methodological approach in different contexts, as well as on the integration of other professionals and waste management from different sectors, broadening the impact and applicability. To introduce improvements to the surface of the material, textures can be designed to increase the emotional appeal of the fabric and contribute to other dimensions of empathy with user preferences in different contexts of use, such as urban and everyday domestic uses, among others.

4. Conclusions

Transdisciplinary is shown to be an essential process for technical innovation and acceptance by both the user and the market, making it possible to address complex problems that would be difficult to solve from a single discipline. In addition, relationships are established between disciplinary and non-disciplinary actors, working through a holistic approach which considers cultural, social, economic, and educational areas. This approach is closely aligned with the principles of the circular economy, showing that the use of wood industry waste not only reduces environmental impacts, but also adds value by converting by-products into useful materials.

The research also highlights the importance of assessing perceived quality and user acceptance, which are both crucial elements in the development of comprehensive and systemic solutions. The transdisciplinary research process facilitates the creation of innovative solutions and generates collective learning among participants, allowing the acquisition of new skills and knowledge that are applicable in other contexts. This experience demonstrates the transformative power of transdisciplinary collaboration in generating positive and empathetic synergies among the actors involved.

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