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Use of Vegetable Waste for New Ecological Methods in Wool Fibre Treatments

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Abstract: In this current research, various amino acids (lysine, betaine, and cysteine) and peptides (oxidised or reduced glutathione) were considered as potential environmentally friendly alternatives to wool bleaching. A greener methodology was also applied to dyeing. Different agro-wastes (red cabbage, peppercorns, and red and yellow onion peels) served as raw pigment materials. The process's efficiency was characterised by the whiteness degree, colour strength, and fastness to accelerated washing and perspiration. A higher whiteness index value was observed in the cysteine-based formulations. The onion peel exhibited significant tinctorial properties due to the presence of some natural mordants. All the proposed treatments were designed with a primary focus on environmental sustainability. These treatments offer a sustainable and environmentally friendly alternative to traditional bleaching and dyeing methods for wool. They reduce costs and energy consumption while creating added value by valorising waste.

Keywords: wool fibre; bleaching; natural dyes; laundering resistance; perspiration resistance

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1. Introduction

Food waste is taking up more and more room in landfills and waste treatment facilities. These days, many residues from the entire food supply chain (FSC) indicate resource waste and environmental issues [1]. Moreover, vegetable waste, like other types of organic waste, can have significant environmental impacts if not appropriately managed [2].

One of the current tendencies is to apply the principles of a circular economy by considering agro-waste as a possible raw fertiliser material. Such initiatives integrate current green attitudes in two ways to reduce the ecosystem impact of this anthropic activity: they decrease the quantity of trash deposited and ensure a durable source of fertilisers [3] or other eco products such as biogas [4]. Such approaches could positively impact potential consumers' views on advanced waste valorisation. [5]. Another proposal targets the capacity for reassignment across the entire food supply chain [6,7].

Recovering bioactive compounds from vegetable waste is an area of growing interest due to its significant potential to add value to what would otherwise be discarded as waste. These compounds, which include antioxidants, dietary fibres, vitamins, minerals, and other phytochemicals, can be utilised across various industries for their health benefits and functional properties [1,8–11]. The textile industry has recently explored the possibility of using food waste as a sustainable raw source for various specific compounds. In this regard, the efficiency of such compounds has been tested in various individual stages as agents for colour fixing [12], for their ability to improve particular properties [13], for

functionalisation [14], and as dye chelators [15–18]. Another possible approach is to extract natural dyes from food waste, such as beetroot [19], onion skins [20], tea [21], tomatoes [22], avocado pits [23], nuts [24], wood [25], husks, etc. Such dyes are environmentally friendly compared to synthetic dyes and can produce various colours [26].

The textile industry has increasingly turned to natural fibres as a sustainable alternative to synthetic materials. Natural fibres are derived from plants [27–29] or animals and have been used in textiles for thousands of years. Currently, the tendency is to use various cellulosic and/or lignocellulosic wastes to obtain woven materials, contributing to footprint reduction [30,31].

Wool is an important animal byproduct. It has been of interest to human society since ancient times to the present due to its versatility. It is a protein-based fibre, with its main applications in the textile industry, and is currently being considered in the construction and remediation fields [32]. The specific types of mammals inhabiting different regions influence the source of wool, which can come from sheep or other animals like goats (cashmere and mohair), rabbits (angora), camels, or alpacas [33]. As a natural material, wool can have both positive and negative environmental impacts throughout its lifecycle, from its production to its disposal. Wool has some environmental impacts, especially on land use and greenhouse gas emissions. Zheljazkov et al. demonstrated the potential efficiency of natural wool waste as a fertiliser resource [34]. Parlato et al., on the other hand, suggested the potential of such products as raw components for structural materials [35]. Such approaches evidence some alternative outputs of wool via integration into the circular economy, contributing to the reduction in its waste footprint. Wool's biodegradability, durability, and potential for sustainable production make it a relatively eco-friendly textile option when managed responsibly. Due to its native origin, it is characterised by a significant proportion of impurities, colour inhomogeneity, and the need to apply various treatments to improve its characteristics for further use in the textile industry. Currently, attention is being paid to different sustainable methods focused on wool's possible rehabilitation [36–39].

Today, the focus is on developing processes and technologies with a minimal environmental impact. It is widely acknowledged that various stages in the textile industry, such as bleaching and dyeing, can be significant sources of pollution. The influence of the first stage, bleaching, on the subsequent dyeing process is particularly pronounced.

In the early years of industrial bleaching, a variety of whitening fluorescent agents (ethylene, styrene, and stilbene) were used based on the photochemical reactions [40]. Their use of wool was needed to produce satisfactory results. Additional auxiliaries (coumarin, sodium bisulphite, and malonic acid) have been used consecutively. Over time, different treatments have proven efficient. Although, at present, the bleaching mechanism is not entirely understood, it is known to be based on disturbing the conjugated double bonds from chromophore groups. The reactions are principally oxidative (peroxides or chlorines) or reductive compounds, along with different auxiliaries (detergents, chelating agents, and activators).

The textile industry is increasingly adopting eco-friendly treatments. Wool photo yellowing, a well-known issue mainly caused by photo-oxidation, can be limited by the utilisation of titanium dioxide nanocrystals [41]. Such treatments can positively influence other fibre characteristics. Using nano-TiO_2, citric acid, and protease improves the wool whiteness index and wettability [42,43]. This shift towards eco-friendly treatments underscores the industry's commitment to sustainability. The green biocatalytic approach is sustained by the technological parameters that assume the sample exposure time decreases at approximately half the speed of oxygenated water treatment and at around 35% of the temperature in the case of whitening in an acidic environment.

Notably, formulations of amino acids and/or enzymes for wool have shown promising results in keratin degradation, such as after the use of L-cysteine, esperase [44], glutathione [45], and enzyme preparations [46] on wool waste. The application of microbial transglutaminase-bentonite has also demonstrated the potential to improve the dyeability of wool [47]. Cysteine, lysine, betaine, or glutathione could serve as promising green

substitutes for traditional bleaching agents, thereby promoting the use of wool as a fibre and not just as a raw material for peptide and/or keratin extraction [44,45,48].

This present study focuses on valorising vegetable waste (red cabbage, red peppercorns, and peels of red and yellow onions) for wool dyeing. Simultaneously, the bleaching treatment is sustainable, utilising several amino acid-based compounds. It proposes eco-friendly textile processing and waste reduction through high valorisation.

2. Materials and Methods

2.1. Materials

The fibre was of the highest quality sheep wool purchased from local farms;

The reagents were of analytical purity and purchased from the reputable supplier Sigma-Aldrich Ltd. (Steinheim, Germany):

- Dyeing solutions were obtained from vegetable wastes, such as red cabbage, red pepper, and red and yellow peel onions, purchased from local producers;
- Washing was conducted with Felosan RG-N (CHT-Group) detergent;
- The bleaching treatment mixture used hydrogen peroxide, sodium silicate, ammonium hydroxide, and acetic acid;
- Mordant was the tannic acid;
- The enzymatic formulations were the pharmaceutical products betaine hydrochloride (bHCl) and lysine (l).

The equipment used is as follows:

- The AATCC standardised Lander-Ömeter with stirring (SDL Atlas Company, Rock Hill, South Carolina —USA);
- A Datacolor 500 spectrophotometer (Datacolor Basel, Switzerland).

2.2. Methods

2.2.1. Wool Pre-Treatment

The raw wool underwent a meticulous pre-treatment process, during which physical (soil) and vegetable (thistles) impurities were manually removed. The experiments were conducted on long wool fibres (**l**) and cut wool fibres (**s**). The cut wool fibre samples were washed with distilled water and an aqueous non-ionic detergent solution at 60 °C, rinsed with tap water, dried at room temperature, and then manually chopped with scissors. The long wool fibres were washed multiple times with tap water and then bleached and dyed, ensuring the highest standards of cleanliness and preparation.

2.2.2. Bleaching Treatment

The wool fibres were treated with various amino acids and/or peptide solutions. The reactions were developed for 24 h at room temperature with magnetic stirring or for 1 h in an ultrasound bath. The ratio of the wool fibres is as follows: the liquid reaction media were (0.25 g of wool in 12.5 mL of H_2O), 1:50. Considering the different mixtures applied, there was 1 g of cysteine, 0.01 g of glutathione reduced or oxidised, and/or 0.5 g of lysine or betaine complex used. Finally, the samples were washed several times with distilled water at 60 °C and dried at room temperature. The working parameters were chosen based on our preliminary tests. They were designed to maximise the targeted features and decrease the possible environmental impact of wastewater. Other criteria were the data presented in the literature, which suggested some optimum limits to increase the formation of interest reactive groups ($-S^-$) and delay the appearance of others (-COOH) [48].

The different amino acids and/or peptides were first solubilised in distilled water. Afterwards, the wool fibres were submerged in the solutions and treated for 24 h under magnetic agitation or one hour with ultrasound.

The wool used for dyeing was bleached using the modified oxidative method with H_2O_2 [49]. The reaction medium contained 3% hydrogen peroxide, 4 g/L of sodium silicate, and 1 g/L of ammonium hydroxide. The fibres-to-liquid ratio was 1:40 for the short wool

fibres and 1:20 for the long fibres. The whitening treatment was performed in the Lander-Ömeter at 95 °C for 60 min. The remaining peroxide was neutralised with 10% acetic acid. All samples were washed multiple times and dried at room temperature.

2.2.3. Dyeing Treatment

The dyeing solutions were obtained from various vegetable wastes, such as the outer leaves of red cabbage, red peppercorns, and peels of red and yellow onions. The ratio of waste to distilled water was 1:10 (10 g of vegetable waste to 100 mL of distilled water). The vegetable wastes were boiled for one hour, and then, the obtained solution was cooled and filtered through filter paper.

Natural dyeing operations were performed with and without mordanting. For dyeing with mordanting, 3% tannic acid was used as a mordant. All samples were dyed at a fibre-to-liquid ratio similar to that used for bleaching treatment using the Lander-Ömeter with stirring at 95 °C for 60 min. The dyed samples were then washed for 10 min at 80 °C in the presence of 1 g/L of Felosan RG-N, rinsed with hot and cold distilled water, and dried at room temperature (Figure 1) [50].

Figure 1. The natural dyeing procedure applied to wool fibres.

2.2.4. Whiteness Degree and Colour Measurements

The AATCC Evaluation Procedure 6-2008 was used to determine the whiteness index and colour strength (K/S) values. The measurements were performed using a spectrophotometer. The colour strength (K/S) value of dyed wool fibres was obtained based on the Kubelka–Munk theory (1) from the reflectance measured at the maximum wavelength (420 nm). The average value of three determinations was considered.

$$K/S = (1 - R)2/2R \quad (1)$$

where K is the absorption coefficient, S is the scattering coefficient, and R is the sample reflectance value at the dominant wavelength.

2.2.5. Colourfastness to Accelerated Laundering

The method followed was the AATCC Test Method 61-2009. The colour strength decreased, and surface modification, due to the detergent and mechanical action, was determined consecutively. The test conditions (1A) are equivalent to repeated hand laundering at low temperatures (40 ± 3 °C). The bath treatment contained 200 mL of distilled water, 10 steel balls, and 0.37 g of WOB powder detergent. The tests were carried out in the Lander-Ömeter with stirring for 45 min, after which the samples were washed with warm and cold distilled water.

2.2.6. Colourfastness to Perspiration

The AATCC Test Method 15-2009 was used. The perspiration solution contained 10 g of sodium chloride, 1 g of lactic acid, 1 g of anhydrous disodium phosphate, and 0.25 g in 1 L of L-histidine monohydrochloride. The measured pH of the obtained solution was 4.3 ± 0.2. The prepared samples were placed in Petri dishes and covered with freshly prepared perspiration solution. During 30 min, they were agitated and soaked to ensure

thorough wetting. After half an hour, all samples were placed between plexiglass plates and kept for 6 h in a horizontal perspiration tester at 38 ± 1 °C in the oven. After the test interval, the samples were kept at 21 °C and 65% relative humidity overnight.

For all colourfastness tests, the samples were placed between two multi-fibres of the test fabrics with filling bands of acetate, cotton, nylon, silk, viscose rayon, and wool. The colour change evaluation was carried out using the industry-standard AATCC Evaluation Procedure 7-2009-Instrumental Assessment of the Change in Colour of a Test Specimen and the AATCC Evaluation Procedure 2-2007-Grey Scale for Staining, ensuring the validity and reliability of the results.

3. Results

The utilisation of natural fibres in the textile industry requires a series of technological treatments to achieve different characteristics. A good result of the dyeing treatment supposes a uniform fibre colour. The consistency of the fibre parameter values plays a significant role in shaping this outcome. It is known that natural fibres have a heterogeneous colour determined by various pigments and/or impurities present. Pigments in natural wool primarily come from the melanin found in the sheep's fleece, which produces various colours in the wool. These natural colours provide an eco-friendly alternative to dyed wool and add unique aesthetic qualities to textiles. However, consumers' preferences for a wide range of coloured wool-made apparel create a demand for developing new eco-friendly dyeing procedures. While the physical impurities can be successfully removed by washing, bleaching is applied to remove the natural pigmentation of wool. Various whitening treatments have been used so far [42,43].

Table 1 comprehensively lists the chemical mixes used for wool bleaching baths.

Table 1. Bleaching baths composition.

Abbreviation	Components
c	the control sample washed with non-ionic detergent, 0.0375 mL/L
w	wool fibres kept in water
GoxbpHCl	oxidised glutathione, betaine + HCl and betaine + pepsin
GredbpHCl	reduced glutathione, betaine + HCl and betaine + pepsin
cbp	cysteine and betaine + pepsin
cbHCl	cysteine and betaine + HCl
cl	cysteine and lysine
Goxl	oxidised glutathione and lysine
Gredl	reduced glutathione and lysine
l	lysine
Goxbp	oxidised glutathione and betaine + pepsin
GoxHCl	oxidised glutathione and betaine + HCl
Gredbp	reduced glutathione and betaine + pepsin
GredHCl	reduced glutathione and betaine + HCl
bp	betaine + pepsin
bHCl	betaine + HCl
Gox	oxidised glutathione
Gred	reduced glutathione
c	cysteine

The results presented in Figure 2 compare the outcomes of wool treatment under magnetic stirring and ultrasound. Ultrasound has a limited effect on the degree of wool fibre

whiteness. Only in two cases (cbp and c) do the recorded whiteness values show an increase for the samples treated under ultrasound. This comparison is particularly important, as the treatment's impact on the fibre structure is negligible [51]; we believe that this contributes to better removal of the physical contaminants and surface lipidic thioester bounds [51]. Additionally, obtaining comparable data supports the use of ultrasound; we can support the use of ultrasound, which should offer environmental benefits due to a reduction in energy consumption and, consequently, lower the costs of the reactions performed under mild conditions. These circumstances open the possibility of using suitable oxidoreductases in the bleaching process—enzymes capable of removing conjugated double bonds present in the chromophore groups.

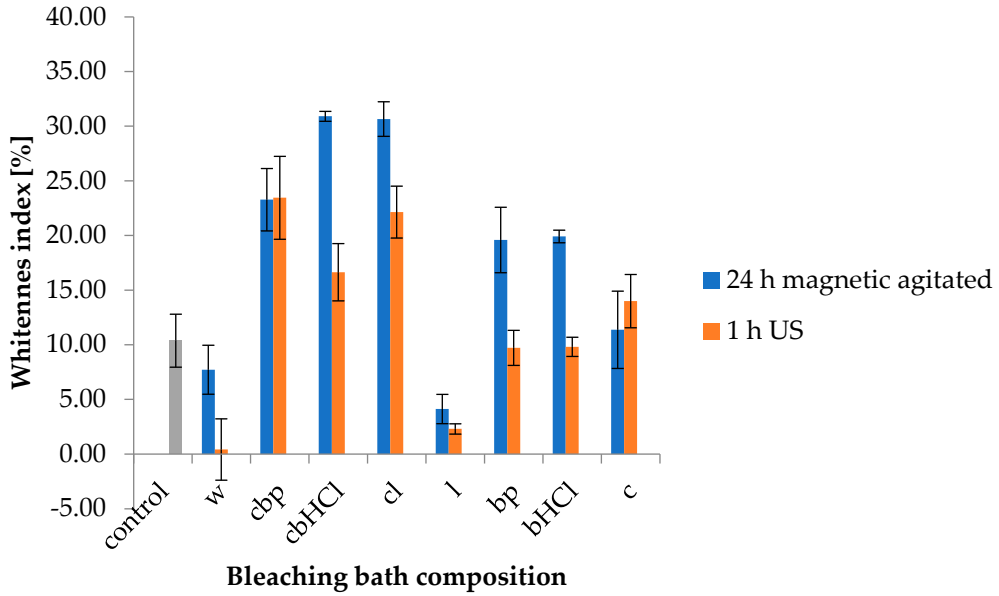

Figure 2. Berger whiteness index after different bleaching treatments: w—water; cbp—cysteine and betaine + pepsin; cbHCl—cysteine and betaine + HCl; cl—cysteine and lysine; l—lysine; bp—betaine and pepsin; bHCl—betaine and HCl; c—cysteine.

Another key aspect that was studied was to optimise the ratio between the treated wool and bath solution, and this was performed by maintaining the bath reactive proportions but modifying the wool fibre quantity (1 or 5 g). As a result, differences in the whiteness index were observed (Figure 3). The samples were kept for 24 h with magnetic stirring in normal daylight radiation. In all treatments containing cysteine, a higher Berger index was recorded. The phenomena may be attributed to the anion RSSR*-radical formation from the cysteine presented in the keratin structure [52].

The use of various reactive baths for wool fibre treatment has shown a distinct advantage in the case of cysteine (Figure 4). The increase in the whiteness index is particularly noteworthy, reaching almost 87% (cbp) compared with the control. This improvement in the whiteness index could be determined by the possible antioxidant activity manifested by exogen cysteine in the reaction media. Matyašovský et al. suggested that mono and dialkyl thioethers groups exhibit such properties [53]. Functional groups could also act as additive and/or synergetic elements, such as the -S^- reacting one formed due to cysteine in a concentration lower than 0.1 M [48]. In addition to enhancing the wool's whiteness, the cysteine pre-treatment improves wettability, softness, and dyeability [48]. In contrast, lower values were observed for the samples treated with glutathione, possibly due to its antioxidant properties.

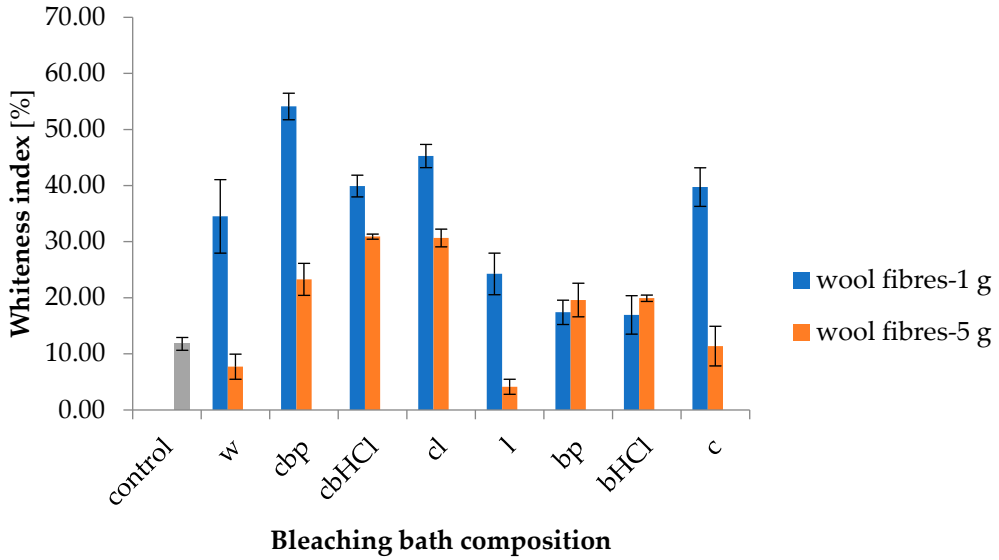

Figure 3. Berger whiteness index for different quantities of treated wool fibres under magnetic stirring: w—water; cbp—cysteine and betaine + pepsin; cbHCl—cysteine and betaine + HCl; cl—cysteine and lysine; l—lysine; bp—betaine and pepsin; bHCl—betaine and HCl; c—cysteine.

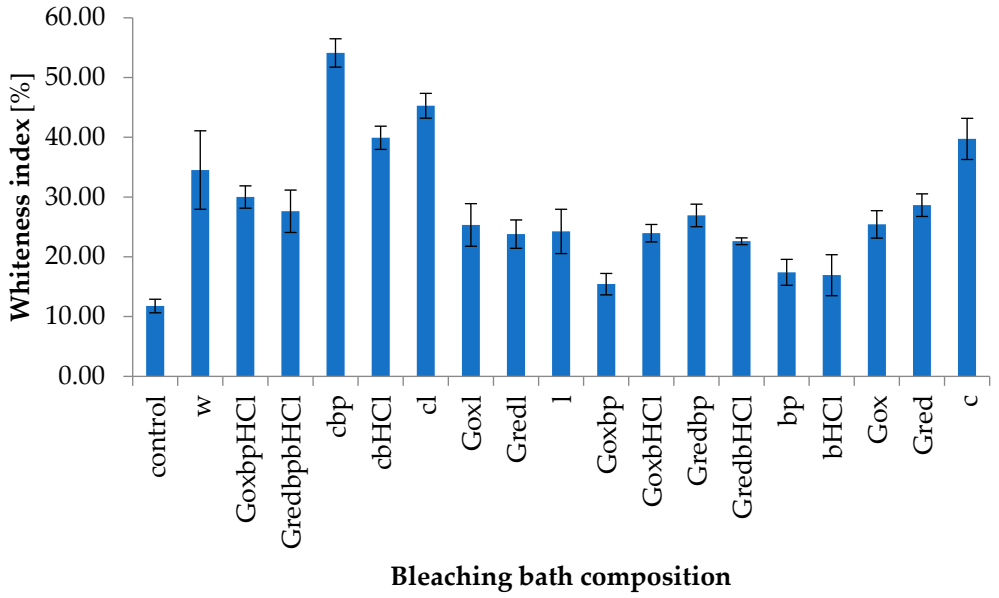

Figure 4. Berger whiteness index of wool fibres treated with different peptidic and aminoacidic solutions: w—water; GoxbpHCl—oxidised glutathione, betaine + HCl and betaine + pepsin; GredbpHCl—reduced glutathione, betaine + HCl and betaine + pepsin; cbp—cysteine and betaine + pepsin; cbHCl—cysteine and betaine + HCl; cl—cysteine and lysine; Goxl—oxidised glutathione and lysine; Gredl—reduced glutathione and lysine; l-lysine; Goxbp—oxidised glutathione and betaine + pepsin; GoxHCl—oxidised glutathione and betaine + HCl; Gredbp-reduced glutathione and betaine + pepsin; GredHCl—reduced glutathione and betaine + HCl; bp-betaine + pepsin; bHCl-betaine + HCl; Gox—oxidised glutathione; Gred—reduced glutathione; c—cysteine.

For colourfastness to perspiration and accelerated laundering evaluation, the ΔE_{CIELab} (the following indicators were used to determine the colour strength: L* assesses the lightness (0–100); a* estimates the change in the colour of the red/green axis; and the b* values reflect the colour variation in the yellow/blue axis) was used to determine the colour differences between the control and the evaluated samples. Figures 5–7 present the colourfastness and staining grades calculated for the tested samples.

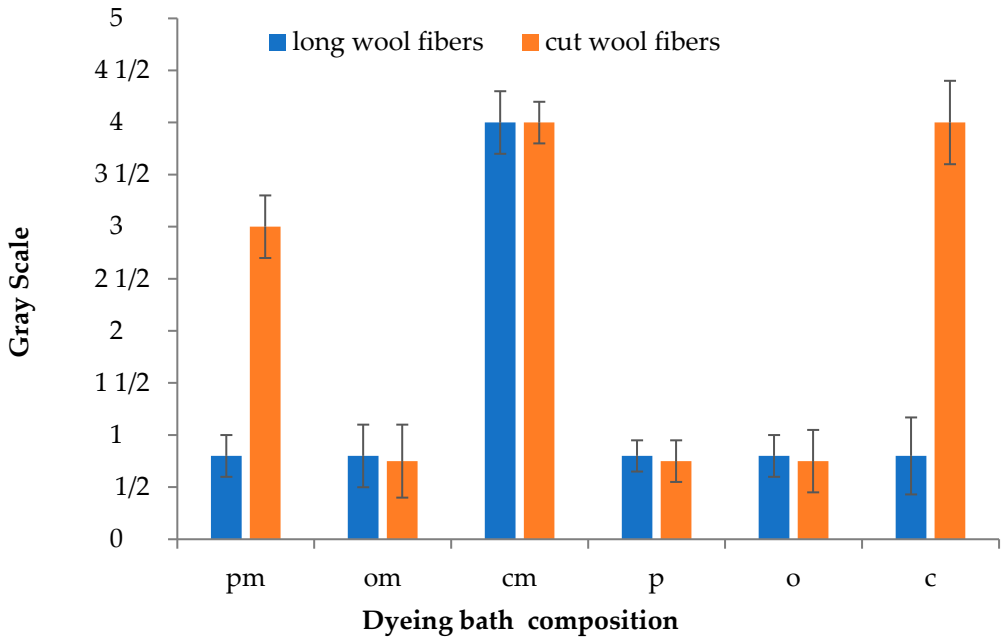

Figure 5. Perspiration colourfastness values were evaluated using the grey scale for colour differences: pm—fibres dyed with pepper and mordant; om—fibres dyed with onion and mordant; cm—fibres dyed with red cabbage and mordant; p—fibres dyed with pepper without mordant; o—fibres dyed with onion without mordant; c—fibres dyed with red cabbage without mordant.

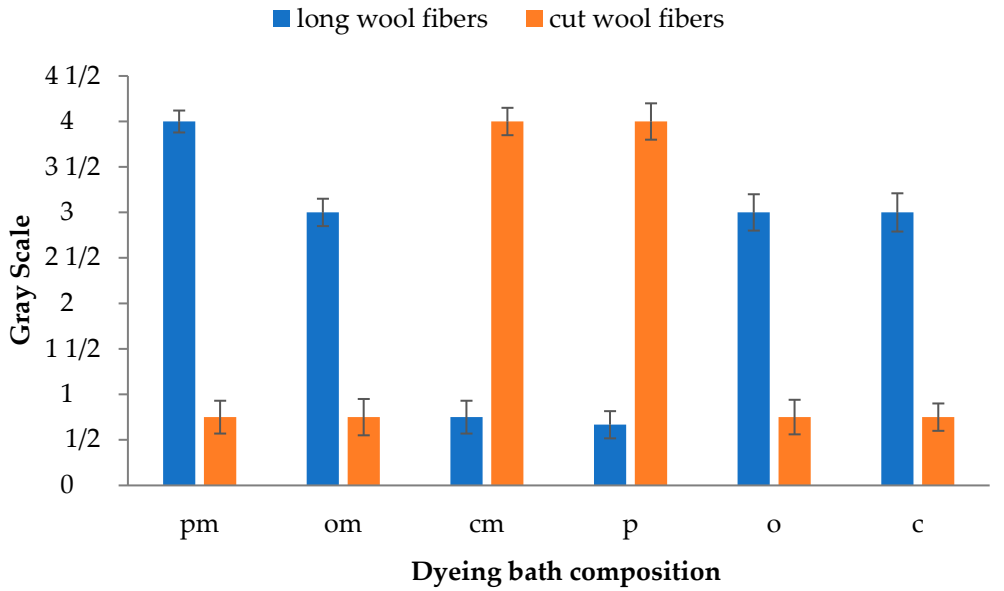

Figure 6. Accelerated laundering colourfastness values were evaluated using the grey scale for colour differences: pm—fibres dyed with pepper and mordant; om—fibres dyed with onion and mordant; cm—fibres dyed with red cabbage and mordant; p—fibres dyed with pepper without mordant; o—fibres dyed with onion without mordant; c—fibres dyed with red cabbage without mordant.

The results obtained highlight the eco-friendly approach that guided all the research. They follow the present trends to propose green alternatives to classical industrial technologies, focusing on finding chemical compound sources by integrating the concept of a circular economy. These study outcomes could provide valuable insights for developing new textile methodologies, focusing on the whitening and dyeing stages. Our proposed alternatives are also supported by other studies presented in the literature [54]. Raw pigment sources are considered as different agro-wastes, so their hydrophilicity is an important

attribute. The possibility of using water as the main solvent has a significant role in the environmental perspective since some of the difficulties posed by wastewater treatment are diminished.

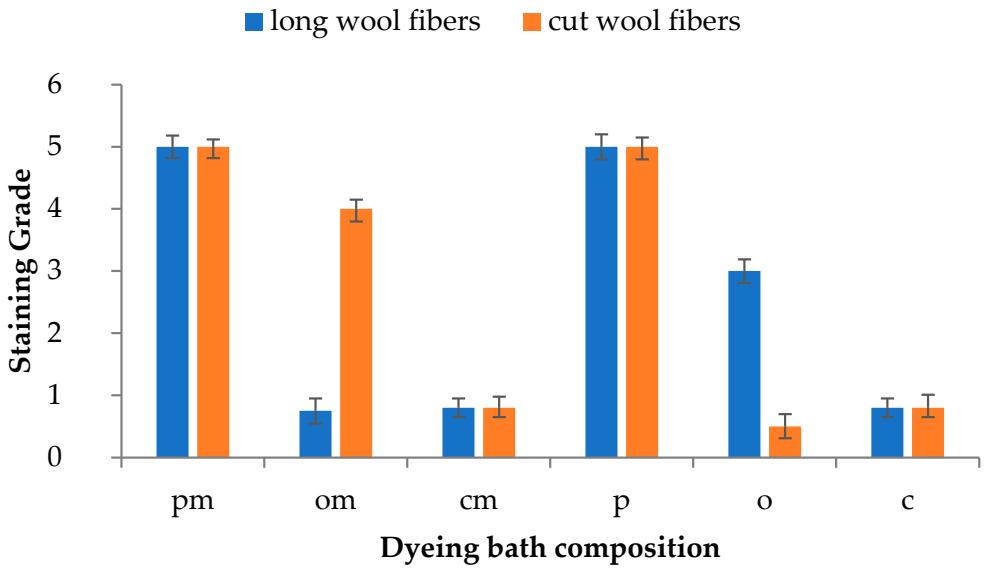

Figure 7. Accelerated laundering colourfastness values were evaluated using the staining grade for colour differences evaluation: pm—fibres dyed with pepper and mordant; om—fibres dyed with onion and mordant; cm—fibres dyed with red cabbage and mordant; p—fibres dyed with pepper without mordant; o—fibres dyed with onion without mordant; c—fibres dyed with red cabbage without mordant.

From the grade values, there can be some differences between the long and cut dyed wool fibres; for the latter, the colour is less affected. The higher decolorisation is shown by the sample dyed with pepper wastes on long fibre (pl). The cut wool fibres dyed with onion (os) had a higher transfer rate. All significant modifications of colourfastness values were obtained in the case of the samples dyed without mordant.

The perspiration tests show good behaviour for all dyeing variants. The GSc values are between 3 and 4/5, representing insignificant lightness changes but modifications for colour strength. Table 2 provides the colourfastness values for the perspiration and accelerated laundering applied to the wool fibres.

This conclusion is supported by the data in Figure 8, where the onion-dyed samples show the highest K/S, which is nearly 10 times higher than those of the other samples.

Table 3 contains the detailed components and the types of wool used in the dyeing baths.

The GSc determination was conducted using the Grey Scale for Colour Change (AATCC Evaluation Procedure 1-2007) and the Instrumental Assessment of the Change in Colour of a Test Specimen (AATCC Evaluation Procedure 7-2009).

Figure 8 shows a slight difference in the colour strength between the samples dyed in the presence of tannic acid (the mordant) and those without it. A significant difference in the K/S value appears between the dyeing variants where different vegetable wastes were used.

The best results were obtained for the wool samples (long or cut fibres) dyed with onion peels in the presence or absence of tannic acid as a mordant. The native mordants in the onion peels, such as the tannins, can explain these results. Saha et al. mentioned a value of around 30 mg/DW of tannic acid equivalent in the analysed samples [55]. These act as natural pigment chelators. Verma et al. also indicated the presence of these molecules in the water-based onion peel extraction media evaluated [56]—the same solvent used in our study. The literature does not indicate evidence that this compound is among the

main constituents of the other agro-waste used. Furthermore, as reported elsewhere, these biomolecules could also enhance the wool's characteristics [57].

Table 2. Colourfastness values.

Sample	Perspiration	Accelerated Laundering	
	GSc	GSc	Staining
pml	4–5	4	5
oml	3–4	3	3–4
cml	4	3–4	4–5
pl	4–5	2–3	5
ol	4–5	3	3
cl	4–5	3	4–5
pms	3	3–4	5
oms	3–4	3–4	4
cms	4	4	4–5
ps	3–4	4	5
os	3–4	3–4	1–2
cs	4	3–4	4–5

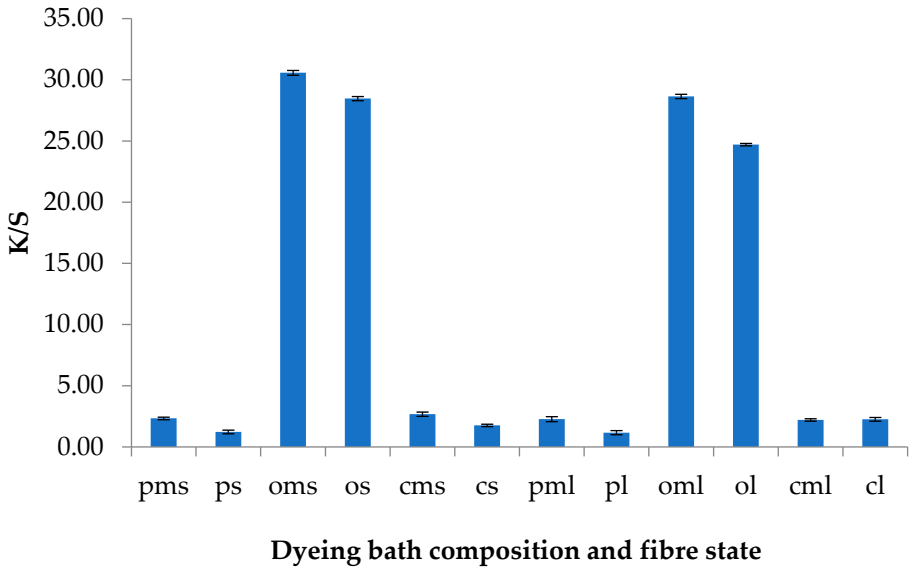

Figure 8. Colour strength was determined for all dyeing treatments used: pml—long wool fibres dyed with pepper and mordant; pl—long wool fibres dyed with pepper without mordant; pms—cut wool fibres dyed with pepper and mordant; ps—cut wool fibres dyed with pepper without mordant; oml—long wool fibres dyed with onion and mordant; ol—long wool fibres dyed with onion without mordant; oms—cut wool fibres dyed with onion and mordant; os—cut wool fibres dyed with onion without mordant; cml—long wool fibres dyed with red cabbage and mordant; cl—long wool fibres dyed with red cabbage without mordant; cms—cut wool fibres dyed with red cabbage and mordant; cs—cut wool fibres dyed with red cabbage without mordant.

These promising results could serve as an investigation of the use of the analysed agro-wastes for dyeing other natural fibres such as linen, hemp, or mixtures. This research could further explore optimising the bleaching formulations. Another aspect that might drive future research is the possible correlations between these natural fibres and the effectiveness of the alternative whitening and tinting processes. The suggestions for potential future

research directions stem from the limitations of this study. In this, the "p" used to represent the possible interactions—additivity, indifference, synergism, or antagonism—between the compounds used for bleaching were not tested.

Table 3. Dyeing bath compositions.

Abbreviation	Components
pml	long wool fibres dyed with pepper and mordant
pl	long wool fibres dyed with pepper without mordant
pms	cut wool fibres dyed with pepper and mordant
ps	cut wool fibres dyed with pepper without mordant
oml	long wool fibres dyed with onion and mordant
ol	long wool fibres dyed with onion without mordant
oms	cut wool fibres dyed with onion and mordant
os	cut wool fibres dyed with onion without mordant
cml	long wool fibres dyed with red cabbage and mordant
cl	long wool fibres dyed with red cabbage without mordant
cms	cut wool fibres dyed with red cabbage and mordant
cs	cut wool fibres dyed with red cabbage without mordant

4. Conclusions

Our investigation focused on a significant concern in the scientific community: proposing sustainable alternatives for vegetable waste valorisation that are theoretical but also have practical applicability in reducing the environmental footprint. At the same time, it suggests an eco-friendly approach to limit the pollutants found in wastewater originating from bleaching and dyeing treatments. The research we present adds to the data currently available in the domain, with the relevance of our findings depending on the availability of each vegetable waste in a given geographical area and the specific properties we aim to enhance [58–60].

This present study considered various possible agro-wastes, such as pepper, cabbage, and onion, while others comprised less analysed alternatives in one study (one, two). One reason for focusing on these vegetables is the large volume of waste they produce. Our gastronomic culture may contribute to the significant presence of these products in the waste stream.

This research focused on two critical steps in textile processing, proposing eco-friendly alternatives. These alternatives could provide treatment options for situations where synthetic pigments may cause an allergenic response.

The data obtained for the whiteness index after using different amino acid and peptide treatments are not just comparable to but often higher than those obtained by the classical method (using H_2O_2 as a bleaching agent). The whiteness index of the samples (Berger) increased for all whitening variants and is similar to those found in the literature: 2.02x (Gredl)–2.55x (GoxbpHCl) compared to 1.94x [43]. The best results were between 3.37x (**c**) and 4.59x (**cbp**), demonstrating the high effectiveness of our proposed treatments.

Although the colour strength of the samples dyed with mordant is generally higher, with differences from the other treatments ranging between 6.87 and 48.46, it is essential to weigh the economic and environmental factors. This perspective is vital in determining the preferred choice, which, in this case, is the dyeing process without mordant. The onion peel dyeing exhibited the best tinctorial properties.

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