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A Study of the Composting Capacity of Different Kinds of Leathers, Leatherette and Alternative Materials

Nima Pourrasoul Sardroudi [1], Sílvia Sorolla [2], Concepció Casas [2] and Anna Bacardit [2,*]

[1] Faculty of Engineering, Ege University, 35040 Bornova, İzmir, Türkiye; 91210000635@ogrenci.ege.edu.tr
[2] A3 Leather Innovation Center, Escola Politècnica Superior, Departament d'Informàtica i Enginyeria Industrial, Universitat de Lleida (UdL), 25006 Lleida, Spain; silvia.sorolla@udl.cat (S.S.); concepcio.casas@udl.cat (C.C.)
* Correspondence: anna.bacardit@udl.cat

Abstract: The leather industry is in the midst of a shift towards sustainability and circular economy principles, placing a strong emphasis on the biodegradability of its products. There has been a notable upswing in the traction gained by eco-friendly leather alternatives. Concurrently, a diverse spectrum of commercial substitutes for conventional leather has surfaced, encompassing a range from synthetic constructs like leatherette to plant-based options. The objective of this study was to evaluate the composting capabilities of genuine leather and three alternatives, namely leatherette, Piñatex®, and Desserto®, in conjunction with leather subjected to treatment with alginate derivatives. The composting evaluation was conducted in accordance with ISO standards, simulating an intensive aerobic composting process. Results revealed that bovine leather samples treated with alginate derivatives underwent complete degradation within 21 to 25 days, and conventional wet-blue production resulted in total degradation after 31 to 35 days. In contrast, vegetable-tanned bovine leather manifested initial signs of degradation after 60 days, but fell short of achieving complete disintegration even after a protracted 90-day incubation period. Alternative materials showed no degradation after the 90-day composting test, indicating a potentially lower degradation capacity compared to leather, likely attributed to the presence of non-biodegradable materials like PU and PVC, among others. The negligible degradation observed in alternative materials after 90 days of composting highlights their inferior composting performance compared to leather.

Keywords: composting; leather; alginate derivatives; leatherette; plant-based materials

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1. Introduction

The leather industry is progressively embracing the principles of sustainability and the circular economy [1]. Leather, being a biodegradable material, exhibits varying degrees of biodegradability depending on the nature of chemicals employed in the manufacturing process [2]. The introduction of new, environmentally friendly leather products into the market is experiencing significant growth, particularly among major companies supplying raw materials to tanneries. According to a market research report published on October 2022, the global plant-based leather market was valued at USD 68 million in 2022 and is projected to reach a value of USD 97 million by 2027 at a compound annual growth rate of 7.5% over the global forecast to 2027.

Concurrently with recent advancements in the leather industry, a variety of commercial alternatives to genuine leather have emerged. These alternatives include synthetic materials manufactured from petroleum-derived products, commonly known as synthetic leather or leatherette, as well as materials positioned in the market as sustainable substitutes for leather or fabric. These new materials are predominantly produced with a combination of biological and petroleum-derived products.

Synthetic leather imitations, predominantly composed of polyvinyl chloride (PVC) or polyurethane (PU) applied onto a backing fabric (either synthetic or natural, like cotton), undergo a surface coating process to enhance their resistance and durability. Both PVC and PU are derived from petroleum, which are not biodegradable, recyclable, nor sustainable.

As for the materials manufactured from by-products of organic origin, the market offers a range of biological-based alternatives to substitute for leather or fabric, including innovative materials cultivated through mycelium growth [3] and advanced materials or composites manufactured from by-products of organic origin across diverse industries, coupled with polymers derived from petroleum or applying biopolymers like polylactic acid.

Mycelium is one of the largest living organisms on the planet, growing through its symbiotic relationship with the material that feeds it, forming interwoven networks of branched fibers [4]. Hyphae are the filaments of the fibrous mycelium and contain elongated cells. The mycelium is composed of 3D networks of hyphae that provide mechanical strength to the entire mycelium [5]. The market offers diverse alternatives produced from mycelium, and one noteworthy example is MycoWorks' Fine Mycelium™, a patented technology revolutionizing material production. Tailored for the fashion, footwear, automotive, and decoration industries, this innovative process guides mycelial cells to grow into unique, interwoven cellular structures, ensuring unmatched strength, durability, and performance. However, the potential of this groundbreaking material to scale industrially faces challenges due to limitations in growth, collection, and the availability of specific mycelium strains [6].

The second family of alternative biological-based materials consists of those manufactured from waste or byproducts containing cellulose. Cellulose is a linear polysaccharide that provides physical strength to plants [7]. The most well-established materials on the market are Piñatex® and Desserto®.

Piñatex® is a non-woven material made from residual pineapple leaf fiber (subjected to various purification treatments) blended with polylactic acid (PLA). The product solidifies through a mechanical process, resulting in a suitable material for use in fashion and accessories, furniture, and automotive applications. Piñatex is marketed as a fully finished product, with an added top coating resembling leather finishing. It does not withstand temperatures exceeding 120 °C. Produced in the Philippines, companies in Spain and Italy apply a conventional finishing layer to Piñatex to give it a leather-like character.

Desserto® is a highly sustainable plant-based material presented as an alternative to leather, made from fibers derived from a species of cactus. The Desserto material is positioned as a leather alternative crafted from fibers extracted from a specific cactus species. Marketed as partially biodegradable, Desserto fulfills the rigorous technical requirements of the fashion industry, leather goods, luxury packaging, and furniture sectors. According to the product's website, the material comprises 90% bio-based compounds. However, the existing literature lacks additional technical details about this innovative material.

In evaluating this new generation of materials, a critical parameter to consider is their biodegradability, a pivotal factor for their successful substitution of leather. Biodegradation involves a chemical process wherein materials are broken down into CO_2, water, and biomass with the assistance of microorganisms. The efficacy of biodegradation depends on various environmental conditions such as location, temperature, humidity, the presence of microorganisms, among others, and the specific environment in which the material is placed (industrial composting plant, garden compost, soil, water, etc.). Consequently, the biodegradation process and its outcomes can exhibit significant variations [8–13].

In this study, the objective is to assess the composting capabilities of three varieties of genuine leather and three leather alternatives: leatherette, material sourced from pineapple leaf fibers, and material derived from cactus fibers. Additionally, a leather treated with a novel system utilizing alginate derivatives has been examined.

2. Materials and Methods

2.1. Materials

To conduct the study, three representative commercial samples from the European high-quality leather market of bovine and ovine origin were chosen. These samples were treated with both chrome and vegetable tanning processes.

As alternative materials, an artificial leather commonly used in furniture upholstery, clothing, and leather goods was selected (leatherette containing PU). Additionally, two alternative materials marketed as sustainable substitutes for leather and fabric, namely Piñatex® and Desserto®, were chosen. Both are derived from the recovery of plant-origin fibers and structured with various polymers such PVC, PU or PLA to attain the required resistances as mentioned above.

The study also includes four tanned leathers from a research and development project, incorporating products designed for increased biodegradability in post-tanning and finishing stages using sodium alginate derivatives. Sodium alginate derivatives (SAD) were produced through a two-hour sonication process of a 2% w/w sodium alginate solution at controlled temperature (50 °C) under atmospheric pressure. Subsequently, ZnO nanoparticles were introduced into the solution through an additional 30 min ultrasonication in the same batch reactor. One of these four tanned leathers was finished using a biodegradable coating based on reutilized collagen gel product [14].

The 10 study samples were identified as follows:

Sample #1. Finished ovine leather chromium tanned;
Sample #2. Finished bovine leather chromium tanned;
Sample #3. Finished bovine leather vegetable tanned;
Sample #4. Leatherette;
Sample #5. Piñatex®;
Sample #6. Desserto®;
Sample #7. Bovine leather tanned with SAD;
Sample #8. Bio-based finished bovine leather tanned with SAD and ZnO nanoparticles;
Sample #9. Bovine leather tanned with SAD and Tara;
Sample #10. Bovine leather tanned with SAD, ZnO nanoparticles and Tara.

2.2. Methods

The evaluation of composting for the diverse array of materials was conducted in accordance with ISO 20200:2015 [15], specifically designed for determining the degree of disintegration of plastic materials under simulated composting conditions in a laboratory-scale test. This method facilitated the assessment of material disintegration when exposed to a composting environment through a straightforward and cost-effective process, adaptable to standard laboratory settings. The approach required only the utilization of standardized and homogeneous synthetic solid waste, comprised of dry, clean, and safe components, devoid of odors or health risks.

The disintegration degree was ascertained following a complete composting cycle, involving the passage of the final matrix through a 2 mm sieve to retrieve non-disintegrated residues. The reduction in mass of the test sample was considered disintegrated material and is used for calculating the degree of disintegration.

For the inoculation of synthetic compost, well-aerated compost from the Jorba composting plant in Spain was employed (Camí Mas Jordà, s/n., 08719 Jorba, Spain, coordinates 41.608848406737124, 1.5112498).

Polypropylene boxes, hermetically sealed to prevent evaporation, served as composting reactors, adhering to the standardized method. Gas exchange is facilitated through 5 mm diameter holes positioned 6.5 cm above the bottom on both sides of the 20 cm box.

The preparation of the composting medium aligned with the stipulations of the standardized method, albeit with specific modifications in component quantities. Notably, a 3.3-fold increase in mature compost for inoculation was incorporated in this study, in accordance with the flexibility afforded by the standardized method. The remaining materials in the final preparation were adjusted proportionally to the final compost weight, as detailed in Table 1. To ensure robust and representative outcomes, the composting experiment was conducted in triplicate, adhering to the recommended practices of the standardized method.

Table 1. Synthetic compost composition.

Material	ISO 20200 [15]—Dry Weight (%)	Study Dry Weight (%)
Sawdust	40	34
Rabbit food	30	27
Mature compost	10	33
Cornstarch	10	2
Saccharose	5	1.5
Corn oil	4	2
Urea (32.5%)	1	0.5
TOTAL	100	100

All materials included in the study were prepared in accordance with the guidelines outlined in the standardized method. Given that the thickness of the samples was below 5 mm, specimens measuring 25 mm × 25 mm × the original thickness were prepared.

Three reactors were set up for testing each material. The ratio between the mass of the material under examination and the mass of the wet synthetic compost was within the range of 0.5–2%.

The mixture was introduced at the base of the reactor, creating a uniform layer. There was no compression of the mixture, allowing for efficient gas exchange within the material bed.

The composting reactors underwent a 90-day maintenance period in the climatic chamber set at 58 °C and 80% relative humidity (RH). Throughout the experiment, the synthetic residue is intended to undergo transformation into compost. The progress of the composting reaction was observed through the examination of the composting material during mixing and the addition of water. The diagnostic parameters, both objective and subjective, to be considered in the experiment include odor, visual appearance, chemical analysis: ratio of total carbon to total nitrogen (C/N) and determination of the degree of disintegration.

Standardized light sieves with mesh sizes of 1 mm and 0.05 mm were utilized. The particle size of the synthetic compost is detailed in Table 2 and the characterization of the compost in Table 3.

Table 2. Particle size of the synthetic compost.

Particle Size	(%)	(g)
≥1 mm	16	281
≥0.05 mm	30	646
≤0.05 mm	53	73

Table 3. Elemental composition of the synthetic compost.

Test	Results	Units	Method
Maturity degree	I (46.9 °C)		Rottegrade test
Organic matter	78.8	%	
Nitrogen Kjeldhal	1.95	%	
C/N ratio	20		

Following the completion of the composting test, an analysis of the corresponding leachates was conducted in accordance with the UNE-EN 12457-4 standard titled “Leaching.

Conformity test for leaching of granular waste and sludges. Part 4: Two-stage batch test with a liquid-to-solid ratio of 10 L/kg for materials with a particle size less than 10 mm (with or without size reduction) [16]".

The preparation of leaching devices involved scaling down to a volume of 200 mL for leachate. To determine the ratio of leachable content for the 10 composts subsequent to the composting study, a specific ratio of 10 L per kg of dry matter was applied, accounting for the moisture calculation associated with each compost. The leaching test was executed with a total volume of 500 mL, utilizing the respective amount of compost sample.

The experimentation involved the utilization of 1000 mL reactors. The leaching process of the compounds was maintained under continuous agitation at a rate of 2 revolutions per minute (rpm) for a duration of 24 h. Upon completion of the designated leaching period, the solutions underwent filtration using a sequence of filters ranging from larger to smaller pore sizes, culminating in a filtration step with a pore size of 0.45 microns. The resultant filtered leachates were then preserved at a temperature of 4 °C to facilitate subsequent testing. The methods to analyze the leachates can be seen in Table 4.

Table 4. Methods to analyze the leachates of the final composts.

Test	Method
pH	UNE-EN ISO 10523:2012 [17]
COD	UNE-EN 77004-1:1998 [18]
BOD (5 days)	ISO 5815-1 [19]
Dry matter	UNE 77030 [20]
Conductivity (25 °C)	UNE-EN 27888:1994 [21]
Nitrogen Kjeldahl	Kit Macherey Nagel
Ammoniacal nitrogen	Kit Macherey Nagel
Chlorides	Ion chromatography
Sulfates	Ion chromatography D
Nitrates	Ion chromatography
Arsenic (As)	Adaptation of IUC 27-2/ISO 17072-2 [22]
Lead (Pb)	Adaptation of IUC 27-2/ISO 17072-2
Cadmium (Cd)	Adaptation of IUC 27-2/ISO 17072-2
Chromium (Cr)	Adaptation of IUC 27-2/ISO 17072-2
Nickel (Ni)	Adaptation of IUC 27-2/ISO 17072-2
Cobalt (Co)	Adaptation of IUC 27-2/ISO 17072-2
Formaldehyde	Adaptation of IUC 19-1-EN ISO 17226-1 [23]
Hexavalent chromium	Adaptation of IUC 18-2-ISO 17075-2 [24]

pH of specimens were carried out according to UNE-EN ISO 10523 by using Crison micro pH 2002 [17].

COD values of specimens were experimented according to the kit instruction by using a digital photomer 500 D Nanocolor with a photometric accuracy of ±1%.

BOD values of specimens were experimented according to the ISO 5815-1 [19]. Primarily, based on the obtained results from COD analysis, appropriate dilution ratios were selected. Therefore, after preparing the solutions, initial oxygen content was measured by OXY 7 Vio machine, and afterward, the samples were incubated in 20 °C for five days. Consequently, final oxygen content were measured with the same method and the differences were calculated.

To determine Kjeldahl Nitrogen, approximately 1 g of leachate samples were weighted into the kjeldahl digester tubes. Later on, 20 mL sulfuric acid (96%) and 4 g catalyst were added in and were let to complete the digesting reaction by increasing the temperature as mentioned in the standard. Therefore, the obtained solutions were distilled and were collected in boric acid solution. Afterward, the final solutions were titrated with 1 N sulfuric acid.

TOC analysis involves oxidizing the organic matter in the sample to carbon dioxide using a high-temperature furnace, typically at around 950–980 °C. The carbon dioxide is then measured using an infrared (IR) detector.

Chlorides can be analyzed by Ion exchange chromatography technique using Waters 2695 equipment. The stationary phase in a cation-exchange column is negatively charged, and chloride ions are attracted to the stationary phase. The mobile phase is typically a buffer solution that is also negatively charged. As the sample solution is pumped through the column, the chloride ions are retained on the stationary phase, while other ions, such as sodium and potassium ions, are washed away with the mobile phase.

The chloride ions can then be eluted from the column with a gradient of increasing salt concentration in the mobile phase. The eluted chloride ions are detected by a conductivity detector, which measures the electrical conductivity of the eluate. The peak height of the chloride ion peak can then be used to quantify the concentration of chloride ions in the sample.

Nitrates and sulfate can be analyzed by Ion exchange chromatography technique, using Waters 2695 equipment.

3. Results and Discussion

Industrial composting, an aerobic process conducted under controlled conditions, plays a crucial role in this context. Factors governing the composting period include temperature (typically 50–60 °C), moisture, oxygen levels, particle size, carbon-to-nitrogen ratio, and the degree of turning. Effective management of these factors can expedite the composting process. It is important to note that the conditions in industrial composting differ from those of home composting, where temperatures may be lower, impacting the overall process.

The outcomes of the industrial composting process are CO_2, water, and compost rich in nutrients. This compost can be utilized in agriculture to enhance soil quality. The advantages of industrial composting are manifold, with the process requiring no chemicals. Additionally, organic recycling contributes to greenhouse gas savings, replacing mineral fertilizers and promoting carbon sequestration in the soil.

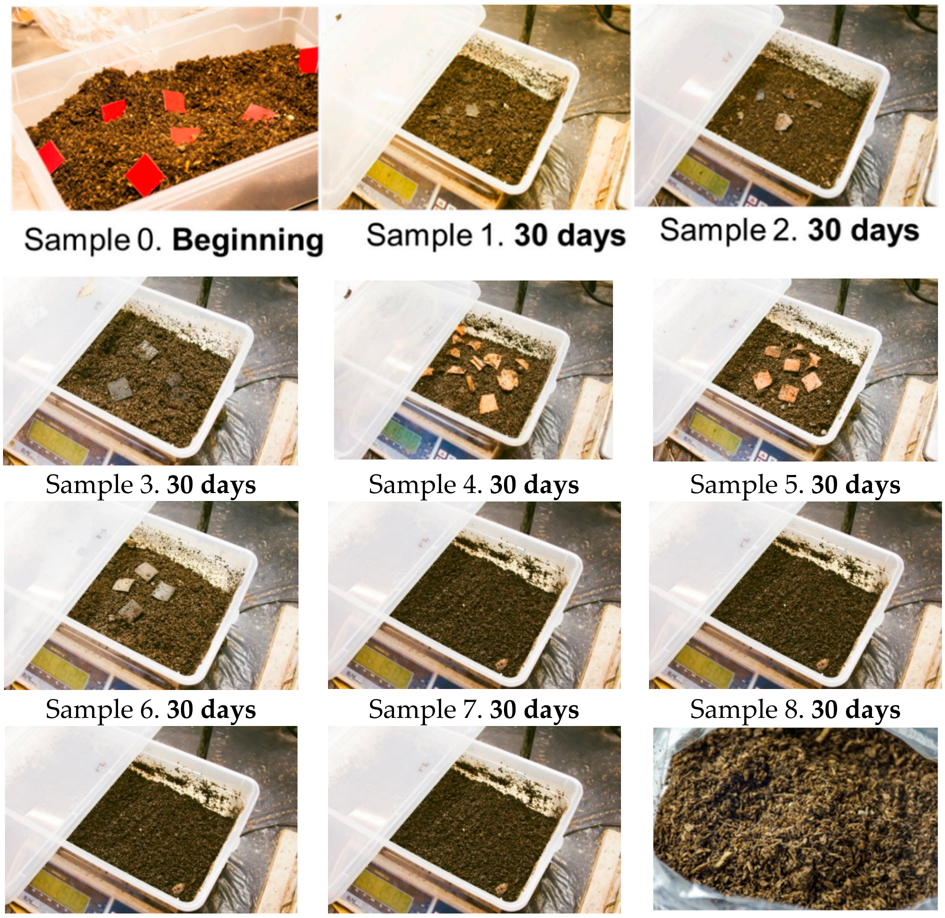
As stipulated in the established Standard, the composting reactors were subject to daily observations. During the initial 21-day period, the emissions included robust acidic and ammoniacal odors. While these odorous manifestations gradually diminished after one month, traces of them endured. The composts underwent a darkening transformation throughout the entirety of the composting process. Figure 1 presents the samples obtained after 30 days of the process, incorporating one sample from the commencement of the study for comparative analysis, as well as the initial synthetic compost.

After 30 days in reactor 1, small fragments of the composted samples of hides and film from the finishing were observed in the process of disintegration. In reactor 2, small pieces of the initial hide and finishing layer were present. In reactor 3, all hide samples showed partial degradation. Reactors 4, 5, and 6 maintained their samples without degradation. preserving their original appearance. Reactors 7, 8, 9, and 10 exhibited complete degradation of the samples.

In Table 5, the degradation time for each of the tested materials can be observed.

Table 5. Degradation times of the materials.

Sample	Degradation Time (Days)
1	35
2	35
3	Starting degradation after 60 days. No degradation after 90 days
4	No degradation after 90 days
5	No degradation after 90 days
6	No degradation after 90 days
7	21
8	25
9	23
10	22



Sample 0. **Beginning** Sample 1. **30 days** Sample 2. **30 days**

Sample 3. **30 days** Sample 4. **30 days** Sample 5. **30 days**

Sample 6. **30 days** Sample 7. **30 days** Sample 8. **30 days**

Sample 9. **30 days** Sample 10. **30 days** **Initial synthetic compost**

Figure 1. Samples after 30 days of composting and initial synthetic compost.

The bovine leather samples subjected to the novel tanning process involving alginate derivatives (samples 7, 8, 9, and 10) exhibited full degradation within 21 to 25 days of initiating the composting test. Bovine and ovine leather samples treated through the conventional wet-blue production and finishing methods displayed complete degradation after 31 and 35 days, respectively. While bovine leather, tanned and finished using vegetable methods, manifested preliminary signs of degradation at 60 days, complete degradation was not achieved even after 90 days.

Non-leather alternatives, such as leatherette, Piñatex®, and Desserto®, showed no indications of degradation after the 90-day composting test. Consequently, it is deduced that these alternatives lack the same capacity for degradation as leather, likely attributable to the presence of fossil-derived products like PU and PVC among others.

Once the composting study was concluded, an elemental characterization of the final 10 compost substrates was carried out. The obtained results can be observed in Table 6.

In order to determine if there are significant differences in the parameters of the final composting substrates, the 10 samples are treated in three different categories. Group 1, consisting of samples 1, 2, and 3, corresponds to the conventional leather category. Group 2, consisting of samples 4, 5, and 6, corresponds to the alternative materials category. Group 3, consisting of samples 7, 8, 9, and 10, corresponds to the novel tanning using alginate derivatives category.

The parameters studied were: Kjeldahl Nitrogen (%), Total Organic Carbon (TOC) %, and C/N Ratio. The mean, variance, and standard deviation were calculated for each parameter and group. An ANOVA test was performed for each parameter using statistical software with a significance level of $\alpha = 0.05$.

Table 6. Characterization of the final compost substrates.

Sample	Nitrogen Kjeldhal (%)	Total Organic Carbon (TOC) %	C/N Ratio
1	2.0	22.5	11
2	2.1	21.5	10
3	2.0	18.6	9.3
4	2.7	21.0	7.7
5	2.3	20.9	9.2
6	2.5	21.6	8.5
7	2.2	21.0	9.8
8	2.8	21.2	7.7
9	2.8	21.7	7.6
10	2.3	21.3	9.5

For each parameter, it was determined whether the p-value of the ANOVA test was less than the significance level. If so, it can be affirmed that there are significant differences in the parameter among the three groups.

In all the parameters analyzed, no significant differences have been observed among the three sample groups.

As evidenced by the results obtained in Table 6, the C/N ratio has decreased from 20 in the initial compost (Table 3) to values ranging between 7.6 and 11. This indicates that the composting process has progressed correctly in all samples.

The results obtained of the characterization of the leachates of the final composts (from Compost C1 to Compost C10) can be seen in Table 7.

Table 7. Characterization of the leachates of the final compost substrates.

TEST	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
pH	8.2	7.5	8.4	7.7	7.6	6.9	7.4	7.3	7.5	7.1
COD (mg/L)	2430	1530	2220	1950	2600	1740	2450	2580	2600	2360
BOD (5 days) mg/L	374	372	118	182	196	123	222	214	192	204
Dry matter (mg/L)	5380	4200	4020	4420	5260	3440	4130	4270	3770	3930
Conductivity (25 °C) µS/cm	5543	5101	4666	4664	3313	3547	3686	3952	3586	3594
Nitrogen Kjeldahl (mg/L)	713	646	524	501	356	157	236	235	198	186
Ammoniacal nitrogen (mg/L)	202	549	342	409	112	84.0	86.8	84.0	98.0	72.8
Chlorides (mg/L)	950	771	710	662	402	458	475	501	475	466
Sulfates (mg/L)	473	523	514	485	471	510	425	364	464	531
Nitrates (mg/L)	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Arsenic (As) (mg/L)	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Lead (Pb) (mg/L)	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Cadmium (Cd) (mg/L)	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Chromium (Cr) (mg/L)	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Nickel (Ni) (mg/L)	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Cobalt (Co) (mg/L)	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Formaldehyde (mg/L)	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Hexavalent chromium (mg/L)	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1

As observed in Table 7, the leachates from all final composting substrates do not contain nitrates, heavy metals, formaldehyde, or hexavalent chromium.

To determine if there are significant differences in the other parameters of the leachates from the final composting substrates, the ten samples are categorized into three groups. Group 1, comprising samples 1, 2, and 3, corresponds to the conventional leather category. Group 2, comprising samples 4, 5, and 6, corresponds to the alternative materials category. Group 3, comprising samples 7, 8, 9, and 10, corresponds to the novel tanning using alginate derivatives category.

There are no significant differences in pH, COD, BOD, sulfates, or dry matter in the leachates. However, significant differences are observed in conductivity, Kjeldahl nitrogen, ammoniacal nitrogen, and chlorides.

Specifically, a higher conductivity is observed in the leachates of samples 1, 2, and 3, corresponding to the conventional leather category. This increase in conductivity may be due to inorganic salts from tanning processes. Specifically, it can be attributed to chlorides, as the leachates from samples 1, 2, and 3 also present a higher quantity of chlorides.

Alginate-treated leather composts (Samples 7–10) present lower levels of Kjeldahl and ammoniacal nitrogen, suggesting efficient degradation and less nitrogen release. Thus, alginate treatment significantly improves leather biodegradability.

Conventional leather is also compostable but might require longer degradation times. Vegetable-tanned leather exhibits limited biodegradability. Non-leather alternatives are not biodegradable under these composting conditions.

Composting leather does not contribute heavy metals or harmful chemicals to the final product. However, these results represent laboratory-scale experiments and may not directly translate to large-scale composting. Further research is needed to assess the environmental impact of leather composting in real-world settings.

4. Conclusions

The leather industry is undergoing a transformation towards sustainability and circular economy principles, with a focus on biodegradability. New environmentally friendly leather products are gaining popularity. Alongside these advancements, various commercial alternatives to genuine leather have emerged, ranging from synthetic materials like leatherette to plant-based options such as Piñatex® and Desserto®.

This study aims to assess the composting capabilities of genuine leather and three alternatives: leatherette, Piñatex®, and Desserto®, along with a leather treated with alginate derivatives. The composting test follows ISO standards, simulating an intensive aerobic composting process.

Results indicate that the bovine leather samples treated with alginate derivatives exhibit full degradation within 21 to 25 days and conventional finished wet-blue production leads to complete degradation after 31 to 35 days. Vegetable-tanned bovine leather shows initial degradation at 60 days, but not complete degradation after 90 days.

Alternative materials, including leatherette, Piñatex®, and Desserto®, show no degradation after the 90-day composting test, suggesting their lower capacity for degradation compared to leather, possibly due to the presence of non-biodegradable materials like PU and PVC, among others.

Elemental composition analysis reveals no significant differences among composts, confirming the composting capacity of both chrome-tanned bovine and ovine leather at a laboratory scale. Leachates from conventional leather-containing composts exhibit higher conductivity, while those from biodegradable leather-treated composts show lower levels of nitrogen compounds.

In summary, the study demonstrates that alternative materials to leather may lack the same capacity for degradation as genuine leather. However, it underscores the importance of exploring sustainable options for the leather industry's future.

As the composting study has been performed with small pieces of materials (2.5 cm × 2.5 cm), the following step is to scale up the composting of all the materials tested at industrial composting plant using pieces of materials of 50 cm × 50 cm, which is approximately a quarter of a full leather.

Every year in Spain alone, around 945 tons of leather scraps in both crust and finished form are generated, ending up in landfills or being incinerated. Since leathers are organic materials, composting can be a very useful process to recycle these waste materials for a new purpose or to generate energy, following the principles of the circular economy.

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