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Sustainable Development of Biodegradable Antimicrobial Electrospun Membranes for Active Food Packaging and Economic Analysis

Emanuela Drago, Roberta Campardelli, and Patrizia Perego**

Electrospinning is a much-explored technique in the membrane fabrication field, particularly in active food packaging. Despite the widespread use of this technique, there remains a significant gap in the literature regarding the actual economic evaluation of the viability of biomaterials compared to traditional plastics. This study seeks to fill this gap by developing electrospun, vanillin-loaded zein membranes to evaluate their efficacy in terms of antimicrobial activity, biodegradability, and economic viability. From a sustainability perspective, the newly developed membranes show an impressive ability to inhibit yeast growth by 75%, with complete degradation observed in only 7 days. This underscores their potential to mitigate environmental impact and promote environmentally friendly packaging solutions to reduce both plastic waste and food loss while maintaining safety and quality. However, the economic sustainability of these membranes is still an open challenge. It becomes clear that the main bottleneck does not lie in the innovative production technology, but rather in the prices of raw materials, particularly natural additives. This underscores the need for supportive measures from institutions to incentivize the transition to sustainable packaging alternatives and the importance of the full circularity concept. This work shows that achieving the European goal of zero plastic waste requires concrete efforts.

1. Introduction

The use of disposable plastic packaging materials usually obtained through the extrusion of thermoplastic polymers has grown enormously over the years, leading to major environmental issues.[1] From the 1950s to 2015, plastics production reached 8.3 billion tons, throwing away ≈6.3 billion in nature, of which 79% ended up in landfills and in natural environments, 12% was incinerated and only 9% was recycled.[2] In recent years the situation has improved, in fact, in 2020, according to Eurostat data, 23% of plastic waste produced in Europe ended up in landfills, 42% was incinerated and 35% was recycled.[3] However, these data also show that the objectives set by the European Union, namely the achievement of 50% plastics recycling by 2025 and 55% by 2030 are still far.[4] Furthermore, the European Food Safety Authority (EFSA) only admits polyethylene terephthalate (PET) as a recycled plastic that is safe for contact with food, as other plastics are rarely used as mono-materials but in the form of blend as well as enriched with chemical additives.[5]

This demonstrates how the use of biodegradable polymers or biopolymers is increasingly becoming a need rather than a choice. However, if the scientific research is frenetic on the formulation of biodegradable materials capable of having performances comparable to those of plastics, the marketing of packaging materials made exclusively from biopolymers is currently very limited.[6–8] To assess whether it is worth investing in the field of food packaging, it is sufficient to observe that, in 2021, the size of the market for this sector closed at 49.8 billion dollars with a growth forecast of 6.4% to reach 72.3 billion dollars by 2027.[9] To be competitive materials with respect to petroleum-derived plastics, it is important that these new packaging solutions are economically viable so that they can be easily integrated into current industrial production processes.[10] The size of the biopolymer film market was equal to ≈4 billion dollars in 2021 with a growth forecast of 8.4% by 2028 precisely due to the growing demand for sustainable packaging.[11] In this context, the concept of food packaging has evolved from passive to active to respond not only to environmental problems through the use of biopolymers but also to reduce food waste often linked to poor management of the distribution chain through the use of natural additives, for example, antimicrobials and/or antioxidants to preserve the shelf-life of perishable foods.[12–17] Considering the manufacturing techniques of flexible films for active

E. Drago, R. Campardelli, P. Perego
Department of Civil, Chemical, and Environmental Engineering (DICCA)
Polytechnic School
University of Genoa
Via Opera Pia 15, Genoa 16145, Italy
E-mail: roberta.campardelli@unige.it; p.perego@unige.it

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packaging, it must be considered that in order to make the use of biopolymers attractive to replace fossil polymers, the possibility of processing them with conventional techniques such as extrusion, molding, calendering, and casting remains fundamental.[18] Speaking of active packaging, it should be considered that the active compounds can be incorporated directly into the polymer matrix and then processed together with the polymer with traditional techniques if they are not thermolabile, or they need to be treated with more innovative techniques, less present on an industrial scale, which work in mild conditions.[19,20] Among the latter, electrospinning is a relatively simple technique that allows nanofibers to be produced from a wide variety of polymers. Using this technique, in fact, fibers with diameters ranging from 2 nm to several micrometers can be produced using polymeric solutions of natural and synthetic polymers.[21,22] This interesting technique has been studied for years in the biomedical field for the production of polymeric scaffolds and is already used on an industrial scale for the production of filter membranes, while it has only recently attracted attention as a film production technique for food packaging.[23–25]

Dedicated to this topic, numerous experimental works can be found in the literature focused on the formulation of porous films enriched with natural compounds for active packaging.[26,27] However, the literature dedicated to the economic evaluation and feasibility of marketing this type of materials is practically nonexistent.[28–31]

Therefore, the aim of this work was to start with an experimental case study to investigate the economic feasibility of a possible pilot-scale production and identify the obstacles to commercialization. In particular, the work aimed to demonstrate the potential of using zein as a biopolymer alternative to plastics to be used on a large scale for electrospinning to produce food packaging that helps to achieve the sustainable development goals (SDG) of the 2030 Agenda, in particular SDG12 of responsible production and consumption. Furthermore, the work aimed to assess whether the bottleneck of these innovative materials, compared to plastic materials, is represented by the raw materials or by the green production technique.

2. Experimental Section

2.1. Chemicals and Electrospinning Components

Zein and vanillin (purity 99%) were supplied by Sigma-Aldrich (Milan, Italy), ethanol was provided by Carlo Erba Reagents, (Milan, Italy), and deionized water was produced in the laboratory of the Department of Civil, Chemical, and Environmental Engineering (University of Genoa, Italy). Commercial *Saccharomyces cerevisiae* was used and a mixture of YPD (Yeast Peptone Dextrose) was purchased by LLG Labware, Meckenheim, Germany.

2.2. Antimicrobial Films Production

The lab-scale electrospinning apparatus was purchased from Spinbow (Bologna, Italy), and it is composed by a high voltage electrical power supplier (PCM series, Spellman, NY, USA), a syringe pump (KDS-100, KD Scientific, Holliston, MA, USA), a needle for solution injection and a static metal plate collector per fibers deposition (25 cm × 25 cm). The apparatus operates under a ventilated hood.[32] This paragraph briefly describes the production process of polymeric membranes via electrospinning, reporting the experimental parameters used. The discussion of process optimization is reported in detail in previous works.[33,34] Briefly, the membranes were produced starting from a polymer solution with a zein concentration equal to 25% by weight compared to the weight of solvent represented by a hydroalcoholic mixture of ethanol at 80% v/v in deionized water. As an antimicrobial agent, vanillin was added to the solution with a concentration equal to 5%, 10%, and 15% by weight compared to the content of zein. The resulting solutions were then processed with a flow rate of 1.2 mL h^{-1}, using a 21-gauge needle, a needle-collector distance of 16 cm, and a voltage of 17 kV, identified as the optimal parameter among those previously investigated. Films were previously characterized in terms of morphology and mean fibers diameter by scanning electron microscopy (SEM) analysis; encapsulation efficiency (EE%) by spectrophotometric analysis at 280 nm; migration test of vanillin in different food simulants, acetic acid 3% w/v and ethanol 10% v/v, evaluated by total immersion method for 24 h following the European Regulation No. 10/2011 on plastic materials and articles intended to come into contact with food.[35]

2.3. Antimicrobial Activity

The antimicrobial activity of vanillin was tested against *Saccharomyces cerevisiae*. This yeast is a non-pathogenic exponent of the eukaryotic microorganism's class, whose uncontrolled growth can induce food spoilage. The antimicrobial activity was evaluated in a liquid medium through the optical density (OD) measurement by means of a spectrophotometer at 650 nm.[36] *S. cerevisiae* was first placed in YPD broth and incubated overnight at 37 °C under shaking in aerobic conditions before its use. The OD of the starting culture was 0.119 nm, corresponding to $\approx 1 \times 10^6$ cells per mL. The analyzed samples were prepared to maintain the ratio between the theoretical content of vanillin and the volume of the culture medium constant and equal to 0.010. The theoretical vanillin concentration present in the samples was: 3 mм for the zein samples loaded with vanillin at 5% w/w, 6 mм for vanillin at 10% w/w, and 9.5 mм for vanillin at 15% w/w. The samples were immersed in the culture medium of YPD broth inoculated with *S. cerevisiae* and placed in an incubator at 37 °C under shaking. The culture medium containing the yeast was used as the control sample while the unloaded zein films were used as the blank sample. The culture medium of each sample was analyzed by spectrophotometer at different time intervals starting from 30 min until reaching the yeast death phase which occurred after ≈26 h.

2.4. Soil Burial Test

Soil burial tests for the assessment of biodegradability in terms of mass loss over time were conducted in triplicate at different time intervals until the complete disappearance of the samples, following the procedure described in the works of

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Figure 1. Examples of electrospinning systems on an industrial scale. Nanospider industrial electrospinning technology of Elmarco (https://www.elmarco.com; http://electrospintech.com/mass-production.html#.Y00hzC0QNAY).

Oberlintner et al. (2021), and Mustapha et al. (2019), with some adjustments.[37,38] In detail, the samples were dried, cut into 3 cm × 3 cm squares, weighed (M0), and placed in open glass bottles filled with commercial gardening soil to a depth of ≈5 cm, half the height of the containers, and left at room conditions. At the fixed time intervals, the samples were removed, cleaned of soil residues, dissolved in 80% v/v ethanol, and centrifuged at 14 000 rpm for 10 min (Alliance Bio Expertise, MF 20-R, France), in order to separate the soil residues from the liquid, composed of the polymer solution and vanillin. The liquid was then dried in an oven for 48 h at 60 °C to evaporate the solvent without further degrading the polymer and the active agent (M1) and was analyzed with gravimetric method.[37] The percentage of biodegradation (DEG) was calculated as reported in Equation (1):

$$\text{DEG}\,(\%) = (1 - \text{M0})/(\text{M1} \times (1 - \text{U}/100)) \quad (1)$$

where U represents the soil moisture which was evaluated gravimetrically by placing the soil samples in oven at 105 °C for 24 h.

The total soluble material content (TSM) of the soil was also evaluated with respect to the solvent used for the test, as reported in Equation (2), a value which was then subtracted from Equation (1):

$$\text{TSM}\,(\%) = (\text{M0} - \text{M1})/\text{M0} \times 100 \quad (2)$$

2.5. Statistical Analysis

Statistica v8.0 software (StatSoft, Tulsa, OK, USA) was used to perform a statistical evaluation of experimental data. Analysis of variance (ANOVA) and Tukey's post-hoc test were carried out to assess the significance of differences among groups with statistical significance considered at a probability value (p) < 0.05.

2.6. B2B Model

The profitability of zein-based polymeric membranes enriched with vanillin as an antimicrobial agent produced by electrospinning was evaluated by adopting a business-to-business model (B2B) to satisfy the request of a hypothetical food company. The membranes produced are intended as patches to be inserted inside the food packages of fresh products. The capital expenditure (CAPEX) and the operating expenditure (OPEX) were estimated to produce a hypothetical 5-year prevision for commercialization. The high versatility of the electrospinning process has already been recognized in terms of process sustainability, food compatibility, and applicability in various industrial sectors. The gain of this process is referred to the one-shot production of packaging materials with an automatized, continuous, and reproducible plant layout. By now, the electrospinning equipment, analyzed in this work, has a Technology Readiness Level (TRL) of 4 (i.e., laboratory validated technology). Considering that there is already industrial-scale equipment used today in other fields than packaging (i.e., YFlow SD, Elmarco reported in **Figure 1**), the project to carry out this industrial process can be easily realized. Therefore, to conduct this economic study, it was decided to use the TRL equal to 7, considering starting from a prototype dedicated to the production of packaging materials.

2.7. Financial Analysis

The financial analysis for the commercialization of biodegradable antimicrobial electrospun patches for packaging needs to be divided into CAPEX and OPEX. CAPEX is linked to the setting up of the electrospinning plant, but also for desks, computers, mobile phones, and all fixed capital investments to start the company. CAPEX amortization was fixed as linear, being the most commonly used method, with a yearly depreciation coefficient of 10% over a period of ≈10 years. Based on literature data, the productivity was fixed at 550 m^2 of films per day and 300 working days per year.[39] The selling price was set at ≈9 euro m^{-2}, equivalent to ≈8 cents per patch, with a typical dimension of 12 cm × 8 cm. The selling price was evaluated considering the realistic retail prices of food products such as red meat, fish, red fruits, etc., for which the patch produced would reasonably weigh ≈2% of the total price of the packaged product.

3. Results

This section is divided into two parts, the first is dedicated to the experimental results of the case study in terms of antimicrobial activity and biodegradability to verify the sustainability

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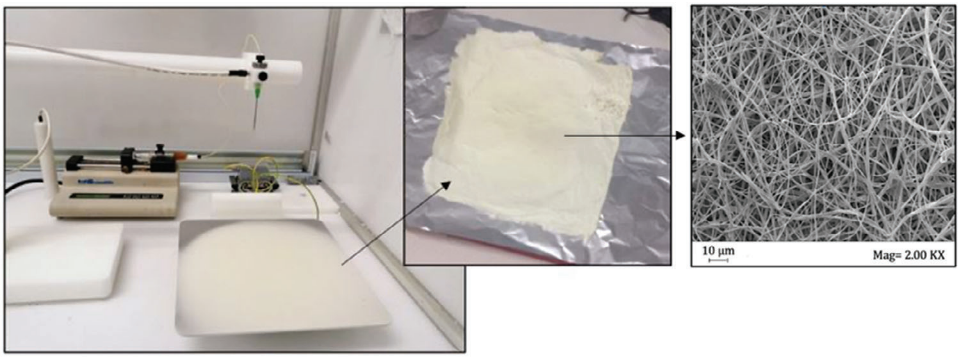

Figure 2. Laboratory-scale electrospinning process to produce antimicrobial zein membranes and SEM image of morphology.

of these materials from an environmental point of view. The second part reports a detailed description of the economic variables and parameters assumed for the evaluation of the business plan for the verification of economic sustainability, a fundamental and innovative aspect of this work conducted to fill the serious gap in the literature. In particular, the CAPEX and OPEX estimates are described, which include costs related to marketing, subcontractors, and personnel, whose values were extrapolated from research conducted on the marketing web. Furthermore, OPEX reports the operating and production costs which were instead calculated on the basis of the experimental results obtained. Finally, the income statement is reported in terms of the profit, loss, and cash flow statements.

3.1. Films Production

The electrospinning process allowed the production of membranes made up of micro and sub-microfibers and, the loading of vanillin did not alter their morphology. **Figure 2** shows an overview of the lab-scale process and the membranes produced, with a SEM image of the obtained samples.

In particular, the obtained electrospun materials were characterized by the random and isotropic orientation of the fibers that showed a ribbon-like structure with an average diameter of 700 nm that did not vary significantly with varying vanillin concentrations. Electrospinning loading of vanillin showed an EE of ≈75% for all concentrations tested, comparable with the results of other work on the loading of active compounds by electrospinning.[40–42] To evaluate the effectiveness of these food contact materials over time, vanillin migration tests were conducted from the zein films using two food simulants: 10% v/v ethanol to simulate hydrophilic foods and 3% w/v acetic acid for foods with acidic pH. The results showed that vanillin is fully released in <48 h and is therefore effective in counteracting the spoilage of fresh foods with a very short shelf-life, such as freshly cut fruit and baked goods. Such rapid-release kinetics are typical of materials produced by electrospinning, which, due to the high surface area exposed by the fibers, allow for instantaneous release, as demonstrated by other authors who measured the migration kinetics of other electrospinning-loaded bioactive substances.[43–45]

As electrospun materials are porous, their gas barrier properties were not evaluated, as they would be completely permeable, as demonstrated by Torres-Giner et al. (2014).[46] Due to this characteristic and on the basis of the poor mechanical properties of electrospun zein,[47] the intended application for this type of material is as a patch to be inserted in contact with the food within the primary packaging. Further details of the process optimization and characterization are reported in previous work.[34]

3.2. Antimicrobial Activity

The results of the antimicrobial tests expressed in terms of OD are reported in **Figure 3**. From the results obtained, it is possible to observe that the control sample (medium with yeast) and the blank sample (unloaded zein) present a similar trend in the growth of the yeast, highlighting that the zein has practically no effect on the yeast, i.e., it does not inhibit it, but it also does not favor its growth as a substrate.

From Figure 3 it is interesting to note that yeast growth was inhibited by the presence of vanillin ($p < 0.05$), and the greatest antimicrobial activity was obtained with the samples produced with the lowest percentage of vanillin, 5%, and 10% w/w. Observing the results obtained after 24 h, corresponding to the maximum growth phase, the reduction of yeast cells was ≈75%, decreasing the number of yeast cells from 15×10^6 cells per mL to 3.5×10^6. Considering the economic aspect, it is interesting to note that electrospun membranes, having a large surface area exposed to the culture medium, are subject to a strong swelling phenomenon which involves a strong contact between the medium and the vanillin contained in the fibrous structure. Therefore, high concentrations of vanillin in zein films are not necessary to exert antimicrobial action against *S. cerevisiae*. The optimal concentration of vanillin to be loaded corresponds to 10% w/w compared to zein, i.e., 6 mM, comparable to that observed in the work of Fitzgerald et al. (2003), in which inhibition of ≈50% of the yeast was achieved by working with a pure vanillin concentration of 5 mM.[48] In the work of Ngarmsak et al. (2006), it was shown that vanillin concentrations of <7 mM were able to completely inhibit yeast grown on fresh mango pieces.[49] Furthermore, Rupasinghe et al. (2006), observed that at vanillin concentra-

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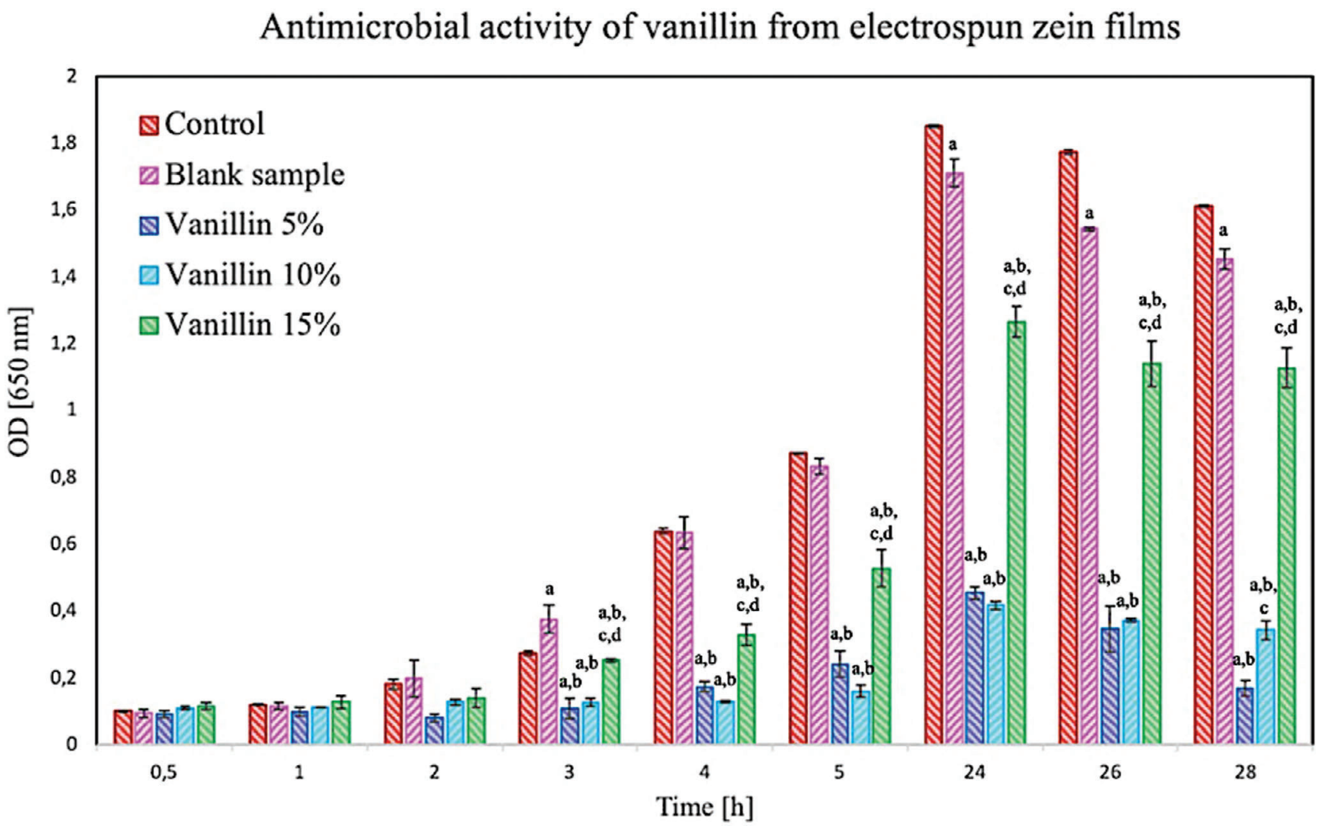

Figure 3. Antimicrobial activity of the different vanillin percentages loaded into zein electrospun membranes. Different symbols indicate statistically significant differences among values over time ($p < 0.05$) of the dataset with different vanillin loading. a) statistically different from a control sample; b) statistically different from the blank sample; c) statistically different from vanillin 5%; d) statistically different from vanillin 10%.

tions of 6 mм, a 73% reduction can also be achieved against *E. coli*.[36]

3.3. Soil Burial Test

In **Figure 4**, it is possible to observe that the soil adhered to the zein films very firmly. For this reason, to evaluate the weight loss of the samples during the burial test, it was necessary to repeat the test at different time intervals, and then dissolve them in the hydroalcoholic solvent and evaluate the weight loss using the gravimetric method. As regard the soil moisture value, it was found to be 66% and this value was not altered after the test. To limit the error potentially due to the soluble part of the soil dissolved in the solvent on the weight values of the samples after the burial tests, the soil solubility in ethanol 80% v/v was calculated, the value of which was subtracted from the masses of the samples degraded.

From the results reported in **Figure 5**, it can be observed that vanillin did not influence the fragmentation kinetics of the films, which for all samples reached values of ≈90% weight reduction in 7 days. This result allows us to affirm that this material, composed of a biopolymer and a natural antimicrobial agent, is completely biodegradable in just one week without altering the soil giving rise to the development of mold.

3.4. CAPEX

The CAPEX represents the value of the assets acquired by the company whose duration is greater than the fiscal year. The CAPEX for biodegradable electrospun patch commercialization are reported in **Table 1**. Five electrospinning machines were hypothesized to work in parallel to guarantee the daily productivity set equal to 550 m^2 day^{-1}, considered adequate for the TRL assumed. The cost assumed for the purchase of a single electrospinning unit represents an average value among the prices of equipment on the market. The hypothesized production system involves a single unit for the preparation of the polymer solution which is then distributed to the machines by means of five feeding valves. The CAPEX evaluation also includes the costs associated with office services and equipment, necessary for starting the business, such as desks, chairs, computers, telephones, and company cars.

3.5. OPEX

The OPEX must include costs related to marketing and logistics management, employee salaries, raw materials for production and maintenance, utilities, and all the expenses necessary to keep the company in activity also considering the inflation

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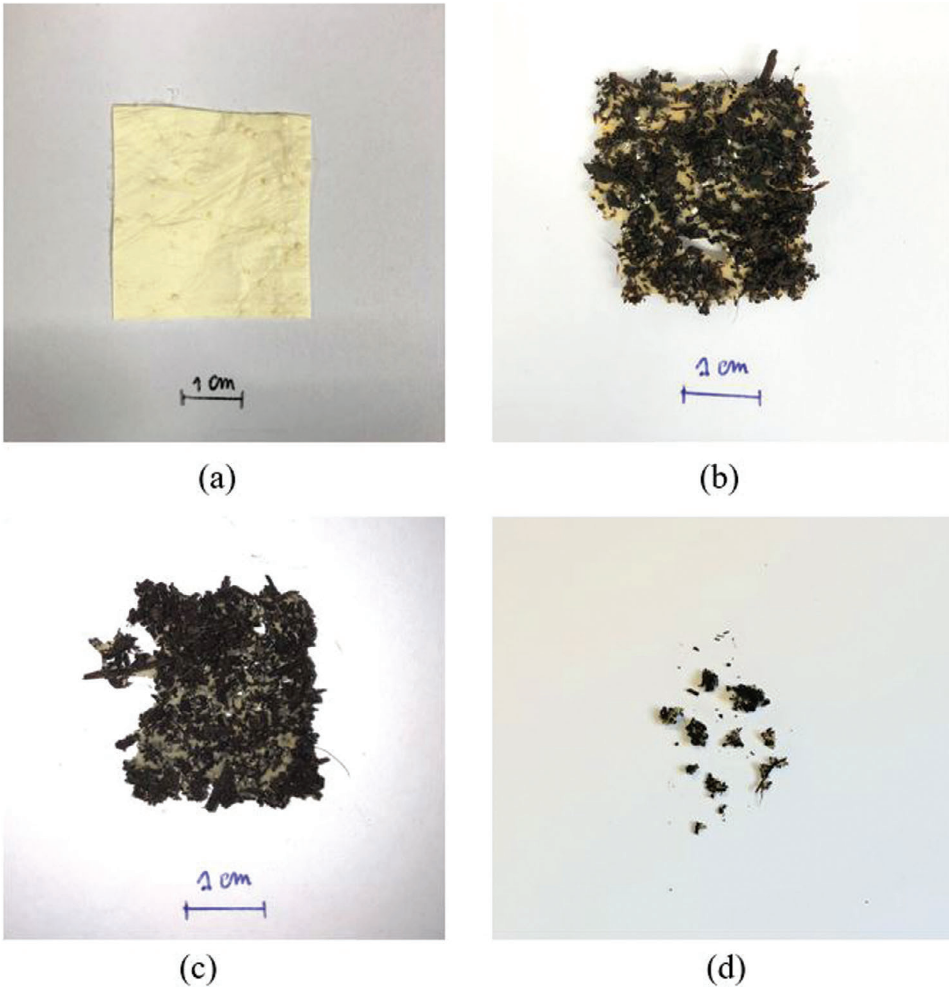

Figure 4. Samples of electrospun zein film during the soil burial test: a) before being buried; b) after 2 days in the soil; c) after 5 days; d) after 7 days.

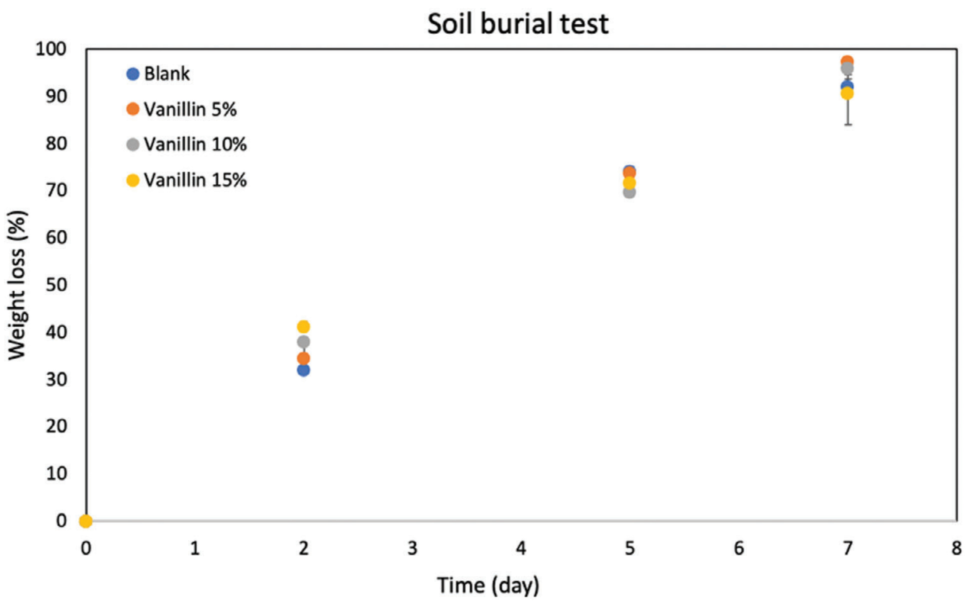

Figure 5. The trend of the percentage weight reduction of the films produced by electrospinning as the vanillin concentration varies during the soil burial test.

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Table 1. CAPEX cost for biodegradable electrospun packaging materials.

Asset Description	unit qty	cost/unit [€]	Total Cost [€]
Electrospinning machine	5	60 000	300 000
Solution preparation system (tanks, pumps, and flowmeters)	1	5000	5000
Solution viscosity measure system	1	1500	1500
Solution feeding system – pump (0,5 KW, Qmax = 900 L h^{-1})	1	450	450
Solution feeding system – valves (solenoid 3/8″)	5	50	250
Solution feeding system – piping (PTFE piping 1/2″, 3/8″)	1	11 000	11 000
Components up-grade (software and hardware)	1	35 000	35 000
Desks and chairs	6	300	1800
Drawers	3	80	240
Personal Computer	3	1000	3000
Automation and Server	1	11000	11000
Company cars	1	20000	20000
Mobile phones – management	2	800	1600
Mobile phones – employees	4	350	1400
Total Assets Cost [€]			39 2240

during the business period (%Δ). OPEX is divided into the following **Tables** 2–5 based on the type of cost.

The total marketing costs, reported in Table 2, are given by the sum of the expenses made annually for events and fairs, communication and promotion strategies via the web.

In Table 3, the costs associated with subcontractors' activities are reported. In particular, in the first year, all the dynamics are foreseen for the definition of the machinery installation contracts and the start-up costs of the company, the second and third years involve transport and installation costs of the system (which occurred in the last months of the first year) and the cost to be considered for the management of the plant automation. While from the fourth year, only the costs related to the maintenance upgrade and current management were considered.

The first part of Table 4, devoted to operating costs, was increased based on forecast inflation. In particular, the quantity of raw materials to be purchased, such as kg of polymer (zein) and antimicrobial agent (vanillin), and liters of solvents, were evaluated based on the experimental data described in paragraph 2.2, compared to the expected productivity of 550 m^2/day for 300 working days. Additionally, approximately an additional 20% was applied as reserve material. The costs associated with raw materials are averaged based on the prices

Table 2. Marketing cost.

Marketing Costs	2023	2024	2025	2026	2027
# of Events & fairs	1	1	2	2	3
Fee	3000	3000	6000	6000	9000
Stand Preparation	7500	8000	8500	9000	9500
Flights, hotels, meals	9600	9600	19200	19200	28800
other costs	960	960	1920	1920	2880
Events & Fairs [€]	21060	21560	35620	36120	50180
Advertising %Δ	0%	2%	4%	6%	8%
Magazines	500	510	530	562	607
TV & Radio	2500	2550	2652	2811	3036
Digital Ads	6000	6120	6365	6747	7286
Brochure & gadgets	1500	2000	3000	3500	4000
Professional Video	2000	2000	4000	4000	6000
Sponsorship	2000	2000	4000	4000	6000
Communication [€]	14500	15180	20547	21620	26930
Costs %Δ	0%	1%	2%	3%	4%
Social media strategy	2400	2424	2472	2547	2649
Web [€]	2400	2424	2472	2547	2649
Marketing Total Costs [€]	37 960	39 164	58 640	60 287	79 758

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Table 3. Subcontractors costs.

Subcontractors	2023	2024	2025	2026	2027
	0%	8%	5%	5%	3%
Project & management	0	40000	2000	0	0
Freight of plant element	0	5000	2500	0	0
Automation & integration costs	0	10 000	9000	4000	4000
Financial Advisor	3000	3240	3402	3572	3679
Legal expenses	3000	3000	2500	1500	1500
Subcontractor [€]	6000	61 240	19 402	9072	9179

reported on the main chemical purchasing websites, such as Merck Millipore, Carlo Erba Reagents, and Thermo Fisher Scientific. Furthermore, the service costs reported in Table 4, were found on the web and were increased based on an increase in turnover.

In Table 5, the personnel costs are reported with the indication of the estimated time frame (%ETF), i.e., the annual commitment of each individual person involved in the business.

Therefore, the first year of investments will be used to obtain customer contracts and installation of the production plant. By the second year, the steady state of production and sale of products will be obtained. By the end of the third year, it will be possible to start to invest again to improve the production.

3.6. Profit and Loss Statement

The profitability of the business in the specific period 2023–2027 can be investigated by the profit and loss statement evaluation. Usually, the profit and loss statement includes both the revenue and the expenses as reported in **Table 6**. In detail, considering that the revenue comes from the sales, the films actually sold were considered 95% of the annual total produced. In the expenses section, all the costs associated with OPEX are reported. The total cost of goods sold (COGS), i.e., the cost of any materials used to obtain the product, was assessed on the basis of the operating conditions (mainly the quantity of raw materials) described in Section 2.2. The gross margin, expressed also as a percentage (GM%) was calculated as the difference between total revenue and total cogs with the costs of not sold and represents

Table 4. Operating and production costs.

Operating	Qty	Cost	Notes	2023	2024	2025	2026	2027
Costs %Δ				0%	8%	5%	5%	3%
Mobile phones	6	120	#of employee	720	778	816	857	883
Power & water supply	1	10 000	yearly	10 000	10 800	11 340	11 907	12 264
Internet	12	100	montly	1200	1296	1361	1429	1472
Bank account	12	5	montly	60	65	68	71	74
PEC	12	30	montly	360	389	408	429	442
Insurance	1	4000	yearly	4000	4320	4536	4763	4906
Software license	12	500	montly	6000	6480	6804	7144	7359
Rent	1	5000	yearly	5000	5400	5670	5954	6132
Mailing services	12	1000	montly	12 000	12 960	13 608	14 288	14 717
Polymers (Zein) [kg]	6336	45.42	yearly	0	287 781	302 170	317 279	326 797
Deionized water [L]	6120	1.6	yearly	0	9792	10 282	10 796	11 120
Ethanol absolute [L]	24336	16.48	yearly	0	401 057	421 110	442 166	455431
Additive (Vanillin) [kg]	350	127.4	yearly	0	44 545	46 773	49111	50 585
Maintenance	1	10%		3934	4249	4461	4684	4825
Operating [€]				43 274	789 912	829 407	870 878	89 7004
Costs %Δ				0%	5%	10%	15%	20%
Accounting, Tax & Legal	1	3000	yearly	3000	3150	3465	3985	4782
Business & strategy	1	3500	yearly	3500	3675	4043	4649	5579
Other services	1	10%	% (other cost)	650	683	751	863	1036
Services [€]				7150	7508	8258	9497	11 396
Operating Total Costs [€]				50 424	797 419	837 666	880 375	908 400

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Table 5. Personnel costs.

Role	Cost 2023	%ETF 2023	%ETF 2024	%ETF 2025–2027	2023	2024	2025	2026	2027
					0%	3%	2%	2%	3%
CEO	80 000	60%	60%	60%	48 000	49 440	50 429	51 437	52 980
Project Manager	35 000	100%	100%	100%	35 000	36 050	36 771	37 506	38 632
Operator	28 800	20%	100%	100%	5760	29 664	30 257	30 862	31 788
Operator	28 800	0%	100%	100%	0	29 664	30 257	30 862	31 788
Adminis-trative	30 000	100%	100%	100%	30 000	30 900	31 518	32 148	33 113
Personnel [€]					118 760	175 718	179 232	182 817	188 302

the overall production efficiency. The long-term debt (LTD) is the principal amount of the loan repayment, the annual increase is due to the French amortization used to calculate the loan, which is considered a constant monthly payment.

The EBITDA (Earnings Before Interest Taxes Depreciation and Amortization) represents the gain before considering the items listed.

Finally, the net profit can be calculated from the total revenues minus the contributions of costs of goods sold and operating expenses. Net profit represents the total amount earned after all expenses have been paid.

3.7. Cash Flow Statement

The evaluation of the cash flow statement allows us to verify, during the development of the business, which have enough money to be able to pay not only materials and assets but also debts and taxes.

The cash flow statement was evaluated considering the cash flows deriving from three areas: operations, investment, and financing, as reported in **Table 7**. The cash flow from operations was calculated as the difference between EBITDA and inventory and taxes. The cash flow from investment was cal-

Table 6. Profit and loss statement.

Profit & Loss	2023	2024	2025	2026	2027
Film produced [m^2]	0	165 000	165 000	165 000	165 000
sell price/m^2	0	9	11	12	13
Film sold [m^2]	0	156 750	156 750	156 750	156 750
Film sold	0	1 410 750	1 724 250	1 881 000	2 037 750
Total Revenue [€]	0	1 410 750	1 724 250	1 881 000	2 037 750
Total Cogs	0	706 017	741 318	778 384	801 735
Cost of not sold	0	37 159	39 017	40 968	42 197
Gross margin [€]	0	667 574	943 915	1 061 649	1 193 818
GM %	0.00%	47.3%	54.7%	56.4%	58.6%
Personnel	118 760	175 718	179 232	182 817	188 302
Events & Fairs	21 060	21 560	35 620	36 120	50 180
Communication	14 500	15 180	20 547	21 620	26 930
Web	2400	2424	2472	2547	2649
Marketing	37 960	39 164	58 640	60 287	79 758
Operating	50 424	54 243	57 331	61 023	64 469
Services	7150	7508	8258	9497	11 396
Subcontractor	6000	61 240	19 402	9072	9179
LTD	33 550	35 750	37 950	40 150	42 350
Total Costs [€]	253 844	373 623	360 813	362 846	395 454
EBITDA	-253 844	293 951	583 102	698 803	798 364
Amortization	35 724	39 224	39 224	39 224	39 224
Depreciation	0	3138	3138	3138	3138
EBIT	-289 568	251 589	540 740	656 441	756 002
Interest	21 450	19 250	17 050	14 850	12 650
EBT	-311 018	232 339	523 690	641 591	743 352
Taxes	0	85 966	193 765	237 389	275 040
Net profit [€]	-311 018	146 374	329 925	404 202	468 312
NP %	0.00%	10.38%	19.13%	21.49%	22.98%

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Table 7. Cash flow statement.

Cash flow	2023	2024	2025	2026	2027
EBITDA	-253 844	293 951	583 102	698 803	798 364
Δ Inventory	0	14 120	14 826	15 568	16 035
Δ Taxes	0	85 966	193 765	237 389	275 040
CFO: Operating Cash Flow	-253 844	193 865	374 510	445 846	507 289
CFI: Investing Cash Flow	-392 240	0	0	0	0
Provision	3904	39 224	39 224	39 224	39 224
Long term debt	550 000	0	0	0	0
Equity injection	75 000	0	0	0	0
Interest	21 450	19 250	17 050	14 850	12 650
CFF: Financing Cash Flow	650 354	58 474	56 274	54 074	51 874
Cash Flow = CFO + CFI + CFF	4270	252 339	430 784	499 920	559 163

culated as the sum of long-term expenses, i.e., all expenses to start the business, that is the previous total assets cost calculated in CAPEX. The cash flow from financing is given by the sum of provision, long-term debt and its interest, and equity injection.

By the previous Tables, it was possible to obtain the following diagrams reported in **Figure 6a–c**.

Figure 6a shows the revenues of the business calculated in Table 5 for the profit and loss statement. In particular, during the first year of the exercise, the aim will be the set-up of the production plant and the statutory requirements. During the second year, it is expected to have 100% of possible production with revenue of 1.4 million € assuming a selling price of 9 € per m^2, this price is equivalent to 8.6 cents per patch for high-density food

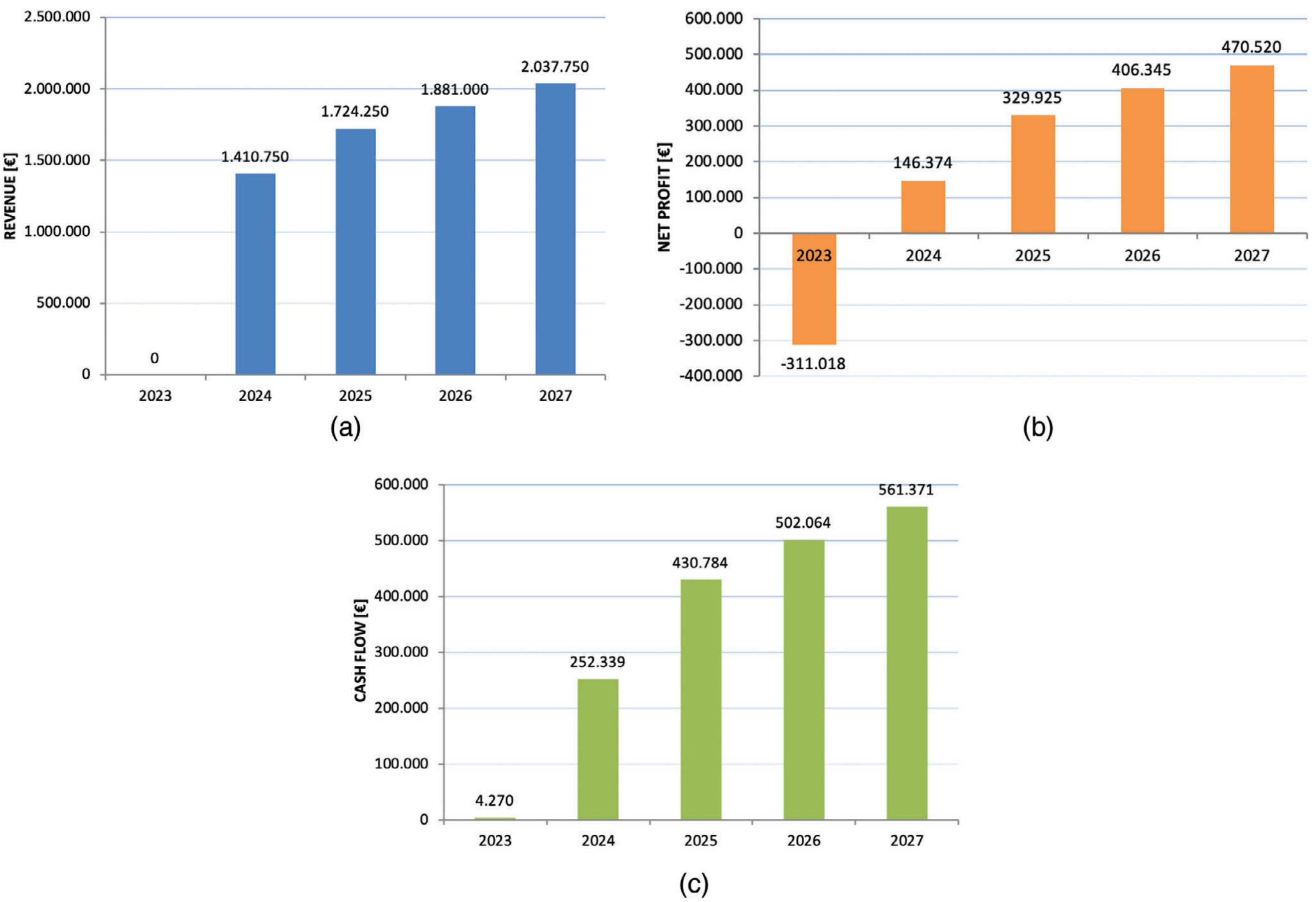

Figure 6. a) Revenues calculated for electrospun packaging materials commercialization (2023–2027); b) net profit diagram; and c) cash flow statement.

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products with a typical price of 3–4 € such as red fruits or red meat package products.

In subsequent years, taking advantage of the regulations against plastic, it will be possible to increase the sale price to 13 € per m^2, reaching 2027 with a turnover of 2 million €, also taking into account the increase in the costs of raw materials and labor.

The net profit graph of Figure 6b, derives from Table 5 and shows that in the first year, the profit will be negative, as there are no sales but only investments and installations. From the second year, the net profit will be positive (representing 30% of the debt) with a forecast of being able to reinvest in the third year to increase production and optimize structural costs.

Figure 6c represents the cash flow statement given by the sum of the three contributions illustrated above. An initial loan of 550 000 € was assumed to generate the cash flow graph.

4. Conclusion

In conclusion, the electrospinning technique for the production of biodegradable antimicrobial membranes has proven to be a sustainable and valid alternative for the production of food packaging. Considering the natural flavor of vanillin, these materials are suitable for fruits, vegetables, and baked goods. Vanillin was shown to be active against *S. cerevisiae* and the large surface area exposed by electrospun materials allows for a membrane capable of reducing 75% of the yeast using low percentages of active agent. From an economic point of view, this is certainly a great advantage considering the high prices of natural raw materials demonstrated with the business plan. From a biodegradability perspective, the samples showed to disappear completely when buried in common garden soil with no obvious effect on soil health, which will however require more in-depth testing. From an economic analysis, these biodegradable antimicrobial membranes produced by electrospinning were found to be a profitable alternative to plastic membranes considering, based on the market, a sales price of 9–13 € m^{-2}. In particular, the product, due to the opacity and porosity resulting from the electrospinning process, can be used as an antimicrobial patch to be placed inside packages measuring ≈12 cm × 8 cm, which will be marketed at ≈8 cents per piece. This price is comparable to that of biodegradable food trays found on the web, which are sold for 8 cents per piece, and is lower than that of waxed paper discs for meat products sold for up to 40 cents per piece. At present, it is difficult to find information on biobased films for food packaging, as they are still scarce on the market, especially in Europe. Obviously, given the current market situation, the price per square meter of polymeric films of fossil origin remains much lower (≈3 € m^{-2} for antimicrobial plastic films), but some considerations must be made about the future trend. First, companies developing plastics are increasingly subject to government restrictions on the production of plastic packaging, single-use packaging has already been banned, and will therefore soon be forced to produce packaging from biodegradable materials with similar characteristics. Second, these alternative packaging materials are bound to initially have a higher cost due to their novelty and low sales volume, but once they reach mass production they will tend to be priced at the same level as traditional materials. Therefore, in the future, these materials produced by electrospinning may be cheaper, and considering the good profitability demonstrated by the business plan, companies currently producing plastic membranes may benefit from the switch to more sustainable materials. Legislative intervention and a clear definition of incentives are certainly necessary to support the transition toward zero plastic waste. Finally, for marketing these materials, it will be necessary to increasingly conduct information campaigns for consumers to increase their awareness regarding purchasing choices and their level of information on the issues of sustainability. Considering the variability of consumer behaviors, it will be necessary to conduct more and more studies and market research to understand consumers' acceptability toward these new packaging systems and also their willingness to pay more for sustainable materials compared to traditional plastic packaging.

The strength of this work is its novelty, in fact, it is not possible to find similar works in the literature for biomaterials for packaging produced with green processes. The limitation is precisely that of not having been able to compare the results obtained with the literature, but the information available on the web was still found and filtered. Therefore, this work helps to fill the gap in the literature by laying the foundations for further studies which could be dedicated, for example, to the economic evaluation of the production of these materials directly from waste, such as corn, recovered by manufacturing companies to encourage the development of a chain of agri-food waste recovery and its transformation into biomaterials for packaging.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

R.C. and E.D. performed conceptualization and validation. E.D. performed methodology, a formal analysis, an investigation, data curation, writing—original draft preparation, writing—review and editing, and visualization. P.P. performed resources. R.C. and P.P. performed supervision and project administration. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

antimicrobials, biodegradability, business plan, electrospinning, food packaging, sustainability

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