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D1.1. REPORT ON IDENTIFICATION OF BIO INDUSTRIAL BIO-BASED VALUE SYSTEMS FOR PROJECT ANALYSIS

MONITORING SYSTEM OF THE ENVIRONMENTAL AND SOCIAL SUSTAINABILITY AND CIRCULARITY OF INDUSTRIAL BIO-BASED SYSTEMS

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Contact person:	Nuria Blasco Lavilla / David Fernández Gutiérrez; david.fernandez@cetenma.es
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Author(s):	Nuria Blasco-Lavilla & David Fernández-Gutiérrez
Contributor(s):	Daniele Spinelli
Reviewer(s):	Björn Krystek & Jennifer Pohlmann
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EXECUTIVE SUMMARY

Transition to a bio-based economy, where biological resources are produced, utilised and regenerated, is necessary to reduce carbon emissions and the demand of non-renewable resources. In this context, BIORADAR project seeks to develop digital monitoring tools to assess material circularity, economic, environmental, and social impacts of industrial bio-based systems. BIORADAR will focus on the fertiliser, packaging and textile sectors due to their economic importance and the expertise of the partners involved.

The first step of the BIORADAR project corresponds to the identification of bioproducts with near-term market potential and their corresponding bio-based value systems. These bio-based value systems will later be evaluated with different circularity, economic, environmental and social indicators to obtain the information required in the development of the digital tools. The present work developed a screening and selection system to choose the bioproducts.

First, a bibliography review was conducted on relevant and recent papers and European projects, using Google Scholar and CORDIS databases, respectively. Bioproducts with direct interest in the fertiliser, packaging and textile sectors were filtered in a preliminary list. Economic and environmental criteria to evaluate their market potential in the near term and suitability for the BIORADAR project were developed using the bibliography. A poll was sent to experts in sustainability and the three bioproduct sectors to rate the importance of the selected criteria. Following the poll results, a decision tree was elaborated to choose the bioproducts, giving priority to the criteria with the highest importance rating like recyclability and availability of local feedstock, over the lowest ones, like the maintenance of properties and the compound annual growth rate. Information to evaluate the bioproducts according to these criteria was obtained from the bibliography and the project FER-PLAY. Bioproducts finally selected were algae biomass, compost, feather meal and wood vinegar for the fertiliser sector; bio-polyethylene, cardboard, paper and polyethylene furanoate for the packaging sector; and bio-nylon, hemp fibre, lyocell and wool for the textile sector.

ABBREVIATIONS

BTI: Bio-based systems Transition Indicators

CAGR: compound annual growth rate

CE: Circular Economy

FDCA: 2,5-furandicarboxylic acid

HMF: 5-hydroxymethylfurfural

LCA: Life Cycle Assessment

LCC: Life Cycle Cost Analysis

MEG: monoethylene glycol

PE: polyethylene

PEF: polyethylene furanoate

PET: polyethylene terephthalate

PHA: polyhydroxyalkanoates

PLA: poly(lactic acid)

PP: polypropylene

S-LCA: Social Life Cycle Assessment

TRL: Technology Readiness Level

WP: Work Package

1. INTRODUCTION

1.1 DESCRIPTION OF THE DOCUMENT AND PURSUE

Nowadays, the continuous increase of the worldwide population causes a high pressure on the natural resources to satisfy the current way of life. To fight against this pressure, the economic system required a new approach, arising the Circular Economy (CE) strategy. This strategy is being adopted and fostered by the European Union to overcome the climate change and environmental degradation by reducing emission and the dependency of external energy and fossil resources (European Commision, 2023; Lokesh, Ladu, & Summerton, 2018).

To achieve a real circular economy, one of the main solutions is the bioeconomy; whose driving force is the use of renewable resources, and the minimisation and valorisation of waste to close the loop making this waste a raw material to manufacture high-added value products. On the other hand, it is interesting to mention that this way to act favours not only on the environment and economy but also on the society enhancing the sustainability and circularity. Within this framework is where **BIORADAR project** emerges, which is focused on three sectors: fertilisers, packaging and textile.

What does **BIORADAR project** propose?

BIORADAR is a Horizon Europe project that takes a system perspective to fill the indicator gap in material circularity, environmental impacts, and social impacts of industrial bio-based systems, and develops a digital monitoring tool for bio-based industries, policymakers, certificate companies, traders and investors. **Figure 1** sums up the project vision.

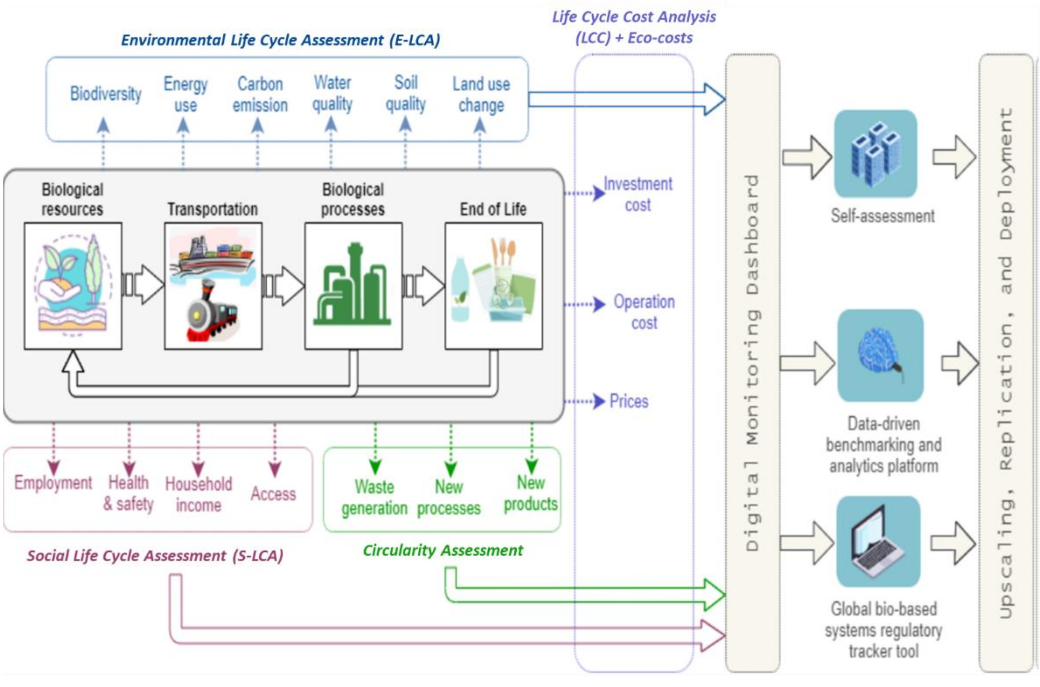

Figure 1 – BIORADAR systems vision

As mentioned, **BIORADAR** is focused on three sectors and the evaluation of bioproducts. However, it is firstly required to select those bioproducts to be evaluated under the project vision, being this the aim of the present report.

In this way, the methodology to select the bioproducts and bio-based value systems that **BIORADAR** will cover in the subsequent steps of the project is displayed throughout this report.

1.2 WPS AND TASKS RELATED WITH THE DELIVERABLE

The present deliverable shows the first task of the BIORADAR project: T1.1 within work package (WP) 1 – Identifying and assessing sustainability aspects (Environmental, Economic, Social) of industrial bio-based systems and embedding them into Bio-based systems Transition Indicators (BTI) framework. Task 1.1 identifies the bioproducts and bio-based value systems that will be worked on in the next technical WPs, from WP2 to WP4.

2. MATERIALS AND METHODS

2.1 REVIEW PROCESS

As mentioned, BIORADAR covers three sectors: fertilisers, packaging and textile. Therefore, this review aimed to identify bioproducts within these three sectors. The selection process to screen and choose the bioproducts was the first step. **Figure 2** displays the process to filter and select the bioproducts to be studied.

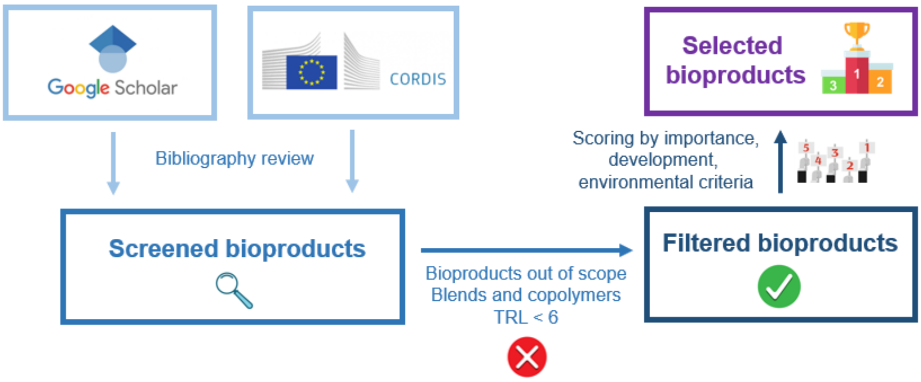

Figure 2 – Overview of the selection process

1) A first search was performed in both Google Scholar (for peer reviewed papers) and CORDIS database (for European projects) using the keywords: “bioproduct” and “bio-based” + sector. For instance, “bioproduct textile” or “bio-based textile”. The first 100 and 50 results from Google Scholar and CORDIS were examined, respectively. The

period covered during this step was from January 2020 to September 2023. In total around 600 papers and 190 projects were checked.

2) From the list obtained in Step 1, any references about a bioproduct related to the three sectors was noted for each paper and European project. In the case of the reviewed European projects, it was differentiated between those specifying a bioproduct and those that did not. In some cases, the results obtained were lower than 50 projects since the beginning of 2020.

3) Out of all identified bioproducts, several of them were discarded based on diverse criteria: i) those bioproducts out of the **BIORADAR** scope for any of the three sectors like dyes, biostimulant microorganisms for agriculture or bioproducts for textile finishing, ii) bioproducts composed of different materials (blends and copolymers), iii) bioproducts with limited development and information (TRL < 6).

2.2 SELECTION CRITERIA

Once some bioproducts were selected as potential ones in the three sectors (56 bioproducts in total), diverse criteria were applied to select the bioproducts to be studied in BIORADAR.

The criteria represent environmental and economic indicators and are similar to criteria used in other studies that assess bioproduct future potential (Biddy, Scarlata, & Kinchin, 2016; Lokesh et al., 2018). A poll was conducted reaching out different experts in order to rate the importance of the different criteria for the bioproduct selection; shown in Section **Error! Reference source not found. Error! Reference source not found.**. Members of the BIORADAR project sent this poll to their network of contacts with expertise in these sectors and on sustainability issues with the aim of obtaining an objective and robust selection system. A total of 17 answers were collected.

Social-related criteria were omitted from the bio-product selection process because of several reasons:

- Lack of standardisation. Guidelines for social indicators are not fully standardized leading to inconsistencies and difficulties in comparing different bio-products.
- Social dimension of bio-products involves multiple stakeholders, encompassing consumers, employees, local communities and society as a whole. Each stakeholder group includes numerous social indicators that must be considered. Acquiring dependable and comprehensive data on these social factors poses a significant challenge.
- Many of these indicators primarily relate to the behaviour of the companies rather than the inherent characteristics of the bio-product itself. Consequently, bio-products within the same sector tend to receive very similar scores, hindering their distinctive assessment.

- Data availability. Gathering comprehensive and reliable data on social aspects, especially for emerging bio-products, can be challenging and social data may not be readily available or may be incomplete, making it difficult to make informed decisions based on this criterion.

- Social data available belongs to country sector-specific data. Since the aim of this task is to characterise and select the most promising bio-products, these data would not achieve that purpose.

Additionally, it is worth noting that a comprehensive Social Life Cycle Assessment (S-LCA) will be conducted for each selected bio-product (T1.4 – Social LCA assessments), resulting in redundant work and overlap in the evaluation process.

2.3 BIOPRODUCT EVALUATION AND SELECTION

Information to evaluate the bioproducts according to the established criteria was obtained from the bibliography, and the FER-PLAY (Horizon Europe ID: 101060426) project in the case of biofertilisers. The different criteria were considered as follows:

- Recyclability: indicated according to the current established recycling systems for a bioproduct. It ranges from "low" = "there is no a proper recycling system yet" to "high" = "the bioproduct already has a good established recycling system". This criterion was not applicable to biofertilisers.

- Availability of environmental information: indicates the availability of Life Cycle Assessment studies for the bioproduct in the bibliography.

- Availability of local feedstock: indicates if the raw material or the most common raw materials used to manufacture the bioproduct are abundantly available in the EU.

- Maintenance of original properties: evaluates the barrier properties, flexibility, and thermal and mechanical properties in the case of packaging bioproducts. To evaluate textile bioproducts mechanical properties and physiological comfort were considered. This criterion was not applied to biofertilisers because of the high variability in their mode of action.

- Ongoing projects: indicates number of projects focused on the development of the bioproduct within each of the three sectors in the CORDIS database. The keywords of the bioproduct and the sector were used in the search. For instance, "paper packaging" was searched. If the bioproduct referred to a blend of materials such as paper packaging with a plastic coating, or the bio-based manufacturing of the product was not specified, such as projects focused on recycling "polyethylene terephthalate", the project was not taken into account.

- <u>Technology Readiness Level (TRL):</u> bioproducts with a TRL lower than six were not considered. To evaluate the TRL of a bioproduct, development of blends was not considered. For example, to evaluate the TRL of poly(lactic acid) (PLA) products in the textile sector, we looked for the TRL of products made purely from PLA. If we could not find enough information to evaluate the TRL of a bioproduct, it was discarded.

- <u>Compound annual growth rate (CAGR):</u> the CAGR of the bioproduct for the near term was looked for in the bibliography.

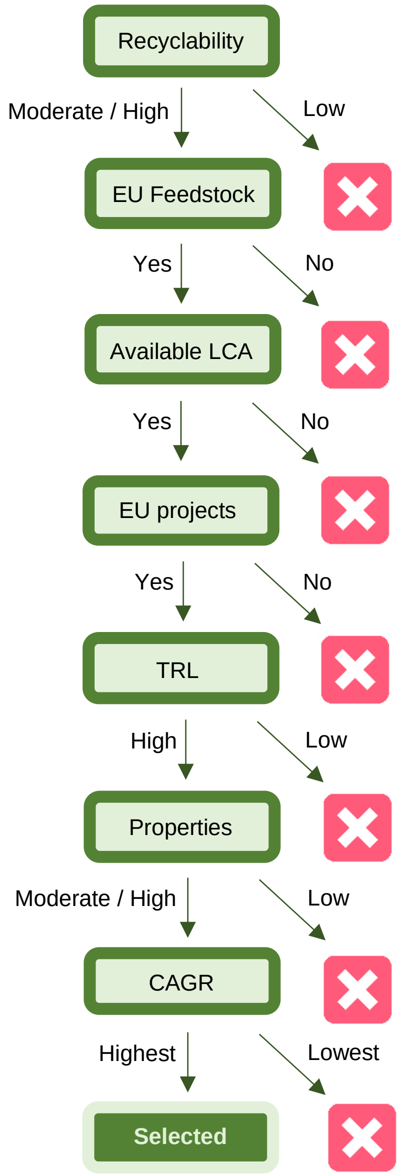

Figure 3 – Decision tree of the bioproduct final selection process

Once the bioproducts had been evaluated for these criteria, a decision tree was followed, discarding or selecting the bioproducts using the different criteria in order of their importance according to the poll conducted **(Figure 3).**

Bioproducts were discarded following the decision tree until four bioproducts were left. If we reached the last step of selection in the decision tree (CAGR criterion), the bioproducts with the highest CAGR were selected.

Once the bioproducts were selected, the main feedstocks used in their production were searched to identify the associated bio-based value systems.

3. RESULTS

3.1 PRELIMINARY LIST OF BIOPRODUCTS

Tables S1-S3 show the lists of bioproducts within the BIORADAR scope and the papers where they were mentioned during the bibliography review.

From the preliminary selection of bioproducts to evaluate, chitin / chitosan was discarded because it was not commonly commercialised as a pure compound but as part of arthropod and fungi residues. Pure chitosan was commonly found as a compound of interest for medical applications.

On the other hand, the textile bioproduct Furoid® was added to the list of bioproducts to evaluate because it was identified from a European project (Furoid, Horizon Europe ID: 101071175) during the bibliography review with the CORDIS database **(Figure 2)**. This was the only bioproduct from the three sectors that was identified through the CORDIS database but could not be found in the search of Google Scholar papers.

The preliminary list of bioproducts with direct interest for the fertiliser, packaging and textile sectors, included 24, 12 and 20 bioproducts, respectively.

3.2 RATING OF SELECTION CRITERIA

Seventeen responses were obtained from four different EU countries. The selection criteria received the ratings indicated in Table 1, with a numerical rating system from 1 to 10, being “1” = “No relevant”, and “10” = Extremely relevant”.

Table 1 – Selection criteria for bioproducts

Criteria	Explanation	Rating
Recyclability	It indicates the difficulty of the bioproduct to be recycled	7.94 (σ = 1.20)
Availability of local feedstock	It indicates the availability of the raw material to obtain the bioproduct in Europe	7.53 (σ =1.85)
Availability of environmental information	It indicates how much a bioproduct has been studied from an environmental viewpoint (LCA)	7.29 (σ =2.52)
Ongoing projects (CORDIS)	It indicates which bioproducts are interesting for the European Community and deserve to be fostered	7.12 (σ =1.60)
TRL (≥ 6)	It indicates the level of development of the bioproduct	6.94 (σ =1.63)
Maintenance of original properties	It indicates that properties in bioproducts are as good as traditional products	6.94 (σ =2.15)
Compound annual growth rate	It indicates the change in the value of a bioproduct over a period of time from an economic viewpoint	6.88 (σ =1.28)

3.3 EVALUATION OF BIOPRODUCTS

Tables 2-4 display the evaluation of the bioproducts for the different criteria, and the criteria that led to select or discard them.

In the case of textile bioproducts, only three bioproducts were selected following the methodology because a biobased polymer (bio-nylon) was added to the final selection to cover different kinds of bioproducts to work on the project.

Table 2 – Evaluation of biofertilisers. Selection steps where they were chosen are highlighted in green, selection steps where they were discarded or no longer considered are highlighted in red, and grey, respectively.

Biofertilisers							
Name	**Recyclability**	**EU Feedstock**	**Available LCA**	**EU projects**	**TRL**	**Properties**	**CAGR**
Algae biomass	Does not apply	Yes	Yes	1	9	Does not apply	6.3 %
Ammonium sulphate	Does not apply	Yes	Yes	0	8	Does not apply	4.9 %
Ashes	Does not apply	Yes	Yes	1	8	Does not apply	No data
Biochar	Does not apply	Yes	Yes	6	7	Does not apply	13.5 %
Black soldier fly frass	Does not apply	Yes	Yes	2	9	Does not apply	No data
Blood meal	Does not apply	Yes	Yes	0	9	Does not apply	3.1 %
Bone meal	Does not apply	Yes	Yes	0	9	Does not apply	4.6 %
Brushite	Does not apply	Yes	Yes	0	7	Does not apply	2.1 %
Cocoa shells	Does not apply	No	Yes	0	9	Does not apply	No data
Compost	Does not apply	Yes	Yes	6	9	Does not apply	4.2 %
Digestate	Does not apply	Yes	Yes	5	9	Does not apply	No data
Feather meal	Does not apply	Yes	Yes	1	9	Does not apply	8.6 %
Hydrochar	Does not apply	Yes	Yes	1	8	Does not apply	No data
Hydroxyapatite	Does not apply	Yes	Yes	0	9	Does not apply	6.5 %
Manure	Does not apply	Yes	Yes	5	9	Does not apply	No data
Poly-γ-glutamic acid	Does not apply	Yes	No	0	9	Does not apply	4.7 %
Soybean meal	Does not apply	No	Yes	0	9	Does not apply	4.2 %
Stabilised sludge	Does not apply	Yes	Yes	2	9	Does not apply	3.5 %
Struvite	Does not apply	Yes	Yes	1	8	Does not apply	No data
Vermicompost	Does not apply	Yes	Yes	0	9	Does not apply	16.7
Vivianite	Does not apply	Yes	Yes	0	6	Does not apply	No data
Wheat straw	Does not apply	Yes	Yes	0	9	Does not apply	9.5 %
Wood vinegar	Does not apply	Yes	Yes	1	9	Does not apply	6.8 %
Wool	Does not apply	Yes	Yes	0	9	Does not apply	3.2 %

Table 3 – Evaluation of packaging bioproducts. Selection steps where they were chosen are highlighted in green, selection steps where they were discarded or no longer considered are highlighted in red, and grey, respectively. Bioproducts were not discarded with the "EU projects" and "TRL" criteria due to the low number of bioproducts that would have remained in the selection process.

Packaging bioproducts							
Name	**Recyclability**	**EU Feedstock**	**Available LCA**	**EU projects**	**TRL**	**Properties**	**CAGR**
Cardboard	High	Yes	Yes	0	9	Moderate	6.2 %
Cellophane	Low	Yes	No	0	9	Moderate	4.9 %
Cellulose-based bioplastic	Low	Yes	Yes	4	9	Low	19.5 %
Fique fibre	No data	No	Yes	0	9	Moderate	No data
Paper	High	Yes	Yes	4	9	Low	2.3 %
Poly(lactic acid) (PLA)	Low	Yes	Yes	2	9	Moderate	13.2 %
Bio-Polyethylene (bio-PE)	Moderate	Yes	Yes	0	9	High	15 %
Polyethylene furanoate (PEF)	Moderate	Yes	Yes	0	8	High	6.4 %
Bio-Polyethylene terephthalate (bio-PET)	Moderate	Yes	Yes	0	8	High	5.2 %
Polyhydroxyalkanoates (PHA)	Low	Yes	Yes	6	7	High	14.3 %
Bio-Polypropylene (bioPP)	Moderate	Yes	Yes	0	8	High	5.6 %
Wood	Low	Yes	Yes	0	9	Moderate	5.2 %

Table 4 – Evaluation of textile bioproducts. Selection steps where they were chosen are highlighted in green, selection steps where they were discarded or no longer considered are highlighted in red, and grey, respectively.

Textile bioproducts							
Name	**Recyclability**	**EU Feedstock**	**Available LCA**	**EU projects**	**TRL**	**Properties**	**CAGR**
Artificial silk	Low	Yes	Yes	0	9	High	18.7 %
Bio-Nylon*	Moderate	Yes	Yes	0	9	Moderate	4.2 %
Bio-Polyethylene terephthalate (bio-PET)	Moderate	No	Yes	2	9	Moderate	11.6 %
Cellulose acetate	High	Yes	Yes	0	9	High	4.4 %
Cotton fibre	High	No	Yes	7	9	High	4.9 %
Flax fibre (linen)	High	No	Yes	0	9	High	7.5 %
Fungal mycelium composite	Low	Yes	Yes	2	7	Moderate	No data
Furoid	No data	Yes	No	1	6	No data	No data
Hemp fibre	High	Yes	Yes	2	9	High	23 %

Ioncell F	High	Yes	Yes	0	7	High	6 %
Jute fibre	High	No	Yes	0	9	High	7.5 %
Lyocell	High	Yes	Yes	1	9	High	8.2 %
Modal	High	Yes	Yes	0	9	High	7.1 %
Nanocellulose	High	Yes	Yes	1	7	High	17.1 %
Poly(lactic acid) (PLA)	Moderate	Yes	Yes	0	7	Moderate	15 %
Ramie fibre	High	No	Yes	0	9	High	2.7 %
Silk	High	No	Yes	0	9	High	6.4 %
Sisal fibre	High	No	Yes	0	9	High	4.2 %
Viscose rayon	High	No	Yes	1	9	High	5.4 %
Wool	High	Yes	Yes	2	9	High	3.2 %

*Bio-nylon was chosen as a bio-based polymer to cover different types of fabrics and because of its availability of feedstock in the EU and its high TRL in comparison with PLA and bio-polyethylene terephthalate (bio-PET).

3.4 BIOPRODUCTS AND BIO-BASED VALUE SYSTEMS TO BE USED IN THE BIORADAR PROJECT

Fertilisers sector

1) Algae biomass: is a source of sugars, amino acids, and plant hormones (Pywowar & Harasym, 2020). Algae can grow in the presence of highly concentrated organic and inorganic chemicals that are toxic to many living organisms. Therefore, algal biomass can be obtained during wastewater treatment and be used as biofertiliser. Although macro- and micro-algae can be used as biofertilisers, the most investigated genus is *Chlorella* sp. (Win, Barone, Secundo, & Fu 2018).

2) Compost: is an accelerated degradation of heterogeneous organic matter by a mixed microbial population in a moist, warm, aerobic environment under controlled conditions (Chen et al., 2012). This decomposition of organic residues improves soil structure and allows the nutrient mobilisation to plants (Sánchez, Ospina, & Montoya, 2017). Composting is the simplest process to treat bio-waste. Bio-wastes with high water content (manure, sewage sludge) are often mixed with fillers to reduce moisture (Witek-Krowiak et al., 2022).

3) Feather meal: chicken feathers waste is a source of keratin and their hydrolysis and digestion with sulfuric acid produces a source of nitrogen that can be applied as foliar fertiliser (Chojnacka, Moustakas, & Witek-Krowiak, 2020). Alternatively, the hydrolysis of feathers keratin with keratinolytic microbes produces amino acids, soluble proteins and peptides that facilitate the growth of microbes in the rhizosphere that improve the assimilation of nutrients by plants (Bhari, Kaur, & Sarup Singh, 2021).

4) Wood vinegar: it is produced during wood and agroindustrial waste gasification as a condensate of the flue gases. Wood vinegar has biostimulant properties for crops due to its content in organic compounds. It contains ketones, organic acids, phenols, carbohydrate derivatives and nitrogenous compounds, among others (Burbano-Cuasapud, Solarte-Toro, Restrepo-Serna, & Cardona-Alzate, 2023).

Packaging sector

1) Cardboard: it is mainly produced from waste paper, which in turn is made of cellulose fibres and different chemicals that determine the properties of paper. For cardboard production, waste products are disassembled in their individual components and materials. After washing these materials, cardboard is produced combining the refurbished parts and substituting non-functional components with similar new ones (Ozola, Vesere, Kalnins, & Blumberga, 2019).

2) Paper: is made of cellulosic fibres that mostly come from wood, but also from rags, flax, cotton linters, and bagasse (sugar cane residue). In the pulping process, lignin and other compounds contained in wood like oleoresins and waxes, are removed. The pulp is then bleached, dried, and further processed, depending on the type of paper to be produced (Bajpai & Bajpai, 2015).

3) Bio-polyethylene (Bio-PE): polyethylene produced from biological sources is currently synthetised from bio-ethanol. First, glucose is obtained from different biological feedstocks like sugar cane, sugar beet, starch crops, and lignocellulosic materials. Glucose contained in the sugar juice and fibres of these materials, is fermented anaerobically to produce bio-ethanol. The obtained ethanol is distilled and ethylene monomers are polymerised into polyethylene to obtain an identical product to polyethylene derived from petroleum (Siracusa & Blanco, 2020).

4) Polyethylene furanoate (PEF): it is produced through the polymerisation of bio-monoethylene glycol (bio-MEG) and 2,5-furandicarboxylic acid (FDCA) derived from first-generation bio-feedstock, such as corn- or wheat-based sugars, or second-generation feedstock, such as waste, wood, wheat-straw, corn stover, or bagasse. Bio-MEG is produced through the fermentation of sugars extracted from biomass into 2G bio-ethanol, that is later transformed into bio-MEG. FDCA can be obtained from 5-hydroxymethylfurfural (HMF), obtainable from fructose and glucose also from biomass sugars (Mendieta, González, Vallejos, & Area, 2022; Reichert et al., 2020).

Textile sector

1) Bio-Nylon: nylon is one of the used polymers (polyamides) in the textile sector. Traditionally, nylon is manufactured from fossil sources and is non-biodegradable, which causes environmental issues at both production process (e.g., generation of N_2O, a greenhouse gas 300 times more potent than CO_2) and the end-of-life stage. To overcome these problems, it is required to use both a renewable raw material and

a sustainable process to manufacture nylon (Hu et al., 2022). It is in this point where bio-nylon arises. Bio-nylon is obtained from renewable sources in the presence of diverse sorts of microorganisms. These green sources can be, for instance, secondary raw materials like lignocellulosic biomass or vegetable oils like castor oil (Biotech Express, 2021). Transforming these green sources into bio-nylon via fermentation, the process can become more sustainable: 100% renewable and biodegradable (Cumbers, 2020).

2) Hemp fibre: it possesses its sustainability as one of the main strengths within the textile sector facing other non-degradable synthetic oil-based fibres such as polyester, acrylic and nylon, which additionally are non-degradable waste (Zimniewska, 2022). On the other hand, it is interesting to mention the impulse provided from the European Commission by developing new strategies like the European Green Deal, which fosters the efficiency of the resources to fight against the environmental impacts. This fact makes hemp fibres a very interesting option to study within the BIORADAR framework.

3) Lyocell: it is a plant-based fibre manufactured of eucalyptus, oak, bamboo and birch trees. Nowadays, it is a popular alternative of the sustainable fashion as it is a biodegradable and compostable material (Lyocell.Info, 2023). According to Choudhury (2017), lyocell shows very low environmental impacts, being significantly more sustainable than synthetic fibres, such as nylon and polyester, and natural fibres like cotton; due to a minor land use, less irrigation and a lower volume of pesticides/fertilisers.

4) Wool: it is a niche product consisting of approximately 1.2% of the market share of the global textile market. From an environmental point of view, wool production consumes far less energy than other widely spread synthetic fibres. In this way, wood is an environment-friendly (natural, renewable and sustainable material) and high-value fibre (Erdogan et al., 2020). Additionally, woollen garments resist the passing of time better than others, which reduces the environmental impacts related to the use stage (Wiedemann et al., 2020).

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5. SUPPLEMENTARY MATERIAL

Table S1 – Bioproducts identified from the bibliography for the fertilisers sector

Biofertilisers	Reference
Algae biomass	Ammar, E. E., Aioub, A. A., Elesawy, A. E., Karkour, A. M., Mouhamed, M. S., Amer, A. A., & El-Shershaby, N. A. (2022). Algae as Bio-fertilizers: Between current situation and future prospective. *Saudi Journal of Biological Sciences*, *29*(5), 3083-3096.
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Bone meal	Brod, E., Øgaard, A. F., Müller-Stöver, D. S., & Rubæk, G. H. (2022). Considering inorganic P binding in bio-based products improves prediction of their P fertiliser value. *Science of the Total Environment*, *836*, 155590.
Brushite	Witek-Krowiak, A., Gorazda, K., Szopa, D., Trzaska, K., Moustakas, K., & Chojnacka, K. (2022). Phosphorus recovery from wastewater and bio-based waste: an overview. *Bioengineered*, *13*(5), 13474-13506.
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Hydrochar	Shi, W., Fenton, O., Ashekuzzaman, S. M., Daly, K., Leahy, J. J., Khalaf, N., Chojnacka, K., Numviyimana, C., Warchoł, J., & Healy, M. G. (2022). Fertiliser equivalent value of dairy processing sludge-derived STRUBIAS products using ryegrass (Lolium perenne L.) and spring wheat (Triticum aestivum).
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Hydroxyapatite	Witek-Krowiak, A., Gorazda, K., Szopa, D., Trzaska, K., Moustakas, K., & Chojnacka, K. (2022). Phosphorus recovery from wastewater and bio-based waste: an overview. *Bioengineered*, *13*(5), 13474-13506.
Manure	Brod, E., Øgaard, A. F., Müller-Stöver, D. S., & Rubæk, G. H. (2022). Considering inorganic P binding in bio-based products improves prediction of their P fertiliser value. *Science of the Total Environment*, *836*, 155590.
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Vermicompost	Chojnacka, K., Moustakas, K., & Witek-Krowiak, A. (2020). Bio-based fertilizers: A practical approach towards circular economy. *Bioresource Technology*, *295*, 122223.
	Churkova, K. (2021). Economic effect of fertilizing with Lumbrex and Lumbrical bioproducts on bird's foot trefoil grassland. *Scientific Papers: Management, Economic Engineering in Agriculture & Rural Development*, *21*(4).
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	Rahimi, A., Amirnia, R., Siavash Moghaddam, S., El Enshasy, H. A., Hanapi, S. Z., & Sayyed, R. Z. (2021). Effect of different biological and organic fertilizer sources on the quantitative and qualitative traits of Cephalaria syriaca. *Horticulturae*, *7*(10), 397.
Vivianite	Witek-Krowiak, A., Gorazda, K., Szopa, D., Trzaska, K., Moustakas, K., & Chojnacka, K. (2022). Phosphorus recovery from wastewater and bio-based waste: an overview. *Bioengineered*, *13*(5), 13474-13506.
Wheat straw	Chojnacka, K., Moustakas, K., & Witek-Krowiak, A. (2020). Bio-based fertilizers: A practical approach towards circular economy. *Bioresource Technology*, *295*, 122223.
	Fabbri, S., Owsianiak, M., & Hauschild, M. Z. (2023). Evaluation of sugar feedstocks for bio-based chemicals: A consequential, regionalized life cycle assessment. *GCB Bioenergy*, *15*(1), 72-87.
Wood vinegar	Obeng, J., Agyei-Dwarko, D., Teinor, P., Danso, I., Lutuf, H., Lekete-Lawson, E., Ablormeti F. K., & Eddy-Doh, M. A. (2023). Bioactivity of an organic farming aid with possible fungistatic properties against some oil palm seedling foliar pathogens. *Scientific Reports*, *13*(1), 1280.
Wool	Chojnacka, K., Moustakas, K., & Witek-Krowiak, A. (2020). Bio-based fertilizers: A practical approach towards circular economy. *Bioresource Technology*, *295*, 122223.
	Izydorczyk, G., Sienkiewicz-Cholewa, U., Baśladyńska, S., Kocek, D., Mironiuk, M., & Chojnacka, K. (2020). New environmentally friendly bio-based micronutrient fertilizer by biosorption: From laboratory studies to the field. *Science of The Total Environment*, *710*, 136061.

Table S2 – Bioproducts identified from the bibliography for the packaging sector

Packaging bioproduct	Reference
Cardboard	Cristofoli, N. L., Lima, A. R., Tchonkouang, R. D., Quintino, A. C., & Vieira, M. C. (2023). Advances in the Food Packaging Production from Agri-Food Waste and By-Products: Market Trends for a Sustainable Development. *Sustainability*, *15*(7), 6153.
Cellophane	Witkowska-Dąbrowska, M., Napiórkowska-Baryła, A., & Świdyńska, N. (2020). Harmonization of criteria and operationalization of sustainable development indicators in the assessment of bioproducts. *Ekonomia i Środowisko*.
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	Wang, J., Euring, M., Ostendorf, K., & Zhang, K. (2022). Biobased materials for food packaging. *Journal of Bioresources and Bioproducts*, *7*(1), 1-13.
Cellulose-based bioplastics	Cristofoli, N. L., Lima, A. R., Tchonkouang, R. D., Quintino, A. C., & Vieira, M. C. (2023). Advances in the Food Packaging Production from Agri-Food Waste and By-Products: Market Trends for a Sustainable Development. *Sustainability*, *15*(7), 6153.
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Table S3 – Bioproducts identified from the bibliography for the textile sector

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Lyocell	Wojnowska-Baryła, I., Bernat, K., & Zaborowska, M. (2022). Strategies of recovery and organic recycling used in textile waste management. *International journal of environmental research and public health*, *19*(10), 5859.
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