D2.2.
Report on evaluation of existing/new metrics on circularity for industrial bio-based systems and propositions of new indicators

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

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DISCLAIMER

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LIST OF ACRONYMS

EU: European Union
CEAP: Circular Economy Action Plan
CBE-JU: Circular Bio-based Europe – Joint Undertaking
SDG: Sustainable Development Goals
EBITDA: Earnings before interests, tax, depreciation and amortization
PAS: Product as a service
ERP: Ecological resource potential
ERB: Ecological resource budget
ESB: Earth system boundaries
EVOH: Ethylene-vinyl alcohol copolymer
HDPE: High-density polyethylene
LCA: Life Cycle Assessment
LDPE: Low-density polyethylene
GWP: Global Warming Potential
UI: Unit impacts
ODS: Ozone depleting substances
PEF: Polyethylene furanoate
PET: Polyethylene terephthalate
PET met: Polyethylene terephthalate metalized
PHA: Polyhydroxyalkanoates
PVOH: Polyvinyl alcohol
r-HDPE: Recycled high-density polyethylene
r-LDPE: Recycled low-density polyethylene
r-PET: Recycled polyethylene terephthalate
Sr-PLA: Starch-based polyactic acid
LCI: Life cycle inventories
WPI: Water-based pressure-sensitive adhesive

EXECUTIVE SUMMARY

Quantitative tools to measure and assess circularity are proliferating at all levels. This report builds on the selection of circular economy indicators proposed in previous BIORADAR deliverable 2.1, assessing and applying them to real-life cases, and complementing them with new indicator propositions that together comprise the BIORADAR product circularity measurement framework.

The BIORADAR project's objective to which this report is linked is to select the most appropriate circularity indicators for the selected bio-based products.

The selected indicators were circular index as a cross-sector indicator, and one sector-specific indicator for each one, namely circularity indicator of nutrient (fertiliser), recycling effectiveness (packaging), and resource pressure (textile). Two types of contrasting characteristics were found, namely aggregating many aspects into a single metric (thus, diluting specificities) or only focusing on a single aspect overlooking others which may be relevant as well. Because of this, the proposition of new indicators was intended to complement, for instance, an aggregated indicator with a specific one and vice versa. Specific aspects on which the spotlight was put were accounting for the biological cycle of materials, the principle of slowing resource loops, and the reduction of virgin materials consumption.

New indicators proposed were biodegradable/compostable content for general use, nutrient slow release index for fertilisers, virgin material consumption index for packaging, and fibre treatment circularity index for textiles.

BIORADAR product circularity measurement framework was applied to 5 fertiliser products, 5 packaging and 10 textile materials, with data sourced from available Life Cycle Inventories. The appropriateness of the framework was validated with manufacturing companies, which found it to be appropriate and useful for the management of sustainable transition.

Upon the usage of the framework to assess the circularity of the targeted materials, the main findings were the appropriateness of the group of indicators selected. In this study, because of the nature of the target materials, circularity during use phase (e.g., sharing, repairing, refurbishing, product-as-a-service, etc.) was considered not applicable, thus excluded from the assessment. In particular, circular index focuses on consumption of non-renewable materials and waste generation, and energy consumption has a practically negligible impact on the indicator. The biodegradable/compostable content contributes by shedding light on the biological cycle.

For fertilisers, the circularity indicator on nutrient focuses completely on process efficiency, and while it is interesting to be complemented by the nutrient slow release index, the data scarcity for the latter is an obstacle for its calculation.

As for packaging, recycling effectiveness turned out to be dependent on simple datapoints available in overall and component-wise mass balances, but restricted to recycling processes. It was complemented by the virgin material consumption index, which shed light on the *other side of the coin* of circularity, which is the consumption of linear (i.e., non-circular) materials.

Regarding textiles, resource pressure was successfully applied, allowing to identify the product that exerts a higher pressure on planetary boundaries. Nevertheless, the results are easier to interpret when fixing a baseline and reporting resource pressure as a variation against it. The fibre treatment circularity index also demonstrated to shed light on a relevant stage of textile production in an appropriate way.

Ultimately, the appropriateness of the framework was identified, both by the analyses it enables, and by the opinions collected from manufacturing companies. The main factor affecting circularity results of the framework is the manufacturing configuration, together with the local or regional circularity installed capacity of the value chain. The use phase was only considered for fertilisers —with limitations— through the nutrient slow release index, but it is also a relevant aspect of packaging and textile products (in contrast with materials, which were assessed hereby). Both the BIORADAR product circularity framework and this first database of results will feed the project’s digital monitoring tool.

1. INTRODUCTION

Having noticed the increasing and alarming consequences of climate change and environment degradation, the European Union has put in place several policy instruments to foster the transition towards a circular economy. The **Green Deal**, presented in 2019, set out the roadmap to **attain natural resources-decoupled economic growth**. It included the goal of reaching climate neutrality by 2050.

Aligned with it, the EU adopted the new **Circular Economy Action Plan (CEAP)** in 2020. It announced initiatives along the entire life cycle of products to **reduce environmental impacts and pressure on natural resources.** Among the key product value chains identified in the CEAP are **packaging, textiles and nutrients** (European Commission, 2020).

A key role among these sectors is played by the concept **Bioeconomy**, which is defined as encompassing "all sectors and associated services and investments that produce, use, process, distribute or consume biological resources, including ecosystem services" (Flachenecker, 2024). Even before the approval of the Green Deal, the EU had released a **Bioeconomy Strategy** (2018), aiming to accelerate the deployment of a sustainable European bioeconomy, contribute towards the Sustainable Development Goals (SDG), and help fulfilling the goals of the Paris Agreement (European Commission, 2022b).

In 2022 a **Bioeconomy Strategy Progress report** was published which identified several gaps among which stand out the need to focus on how to **better manage land and biomass needs**, and the need to work on **more sustainable consumption patterns** (European Commission, 2022a).

Such a transition requires not only of strategies and roadmaps, but also **monitoring systems and measurement frameworks**. While some work has been undertaken to measure advancements towards circular bioeconomy at the macro level (countries and regions), **management tools at the micro (product) level are still not well developed** (Bianchi et al., 2024). As a result, policy makers can affirm that their constituencies have done substantial advancements (Kardung & Drabik, 2024), but **business managers and investors** lack indicators and tools to assert the same, leaving them **without key information needed to better steer their firm's transition**.

BIORADAR —as an initiative supported within EU efforts to foster circular economy, particularly through the Circular Bio-based Europe – Joint Undertaking (CBE-JU)— **strives to contribute to the development and positioning of monitoring tools applied to bio-based products**, specifically in the sectors of fertilisers, packaging and textiles.

1.1 DESCRIPTION OF THE DOCUMENT AND PURSUE

This report presents the **results of assessing the product circularity indicators** that were previously selected in *Deliverable 2.1 – Report on identification of circularity indicators methodologies for industrial bio-based* *systems*, calculating them for target bio-based products, and complementing them with the **proposal of new indicators**.

Both existing and proposed indicators comprise **BIORADAR's bio-based circularity measurement framework**.

BIORADAR has a primary **focus on three key industry sectors: fertilisers, packaging, and textiles**. Among them, four products per category were selected based on environmental and economic criteria, whose methodology is shown in *Deliverable 1.1 – Report in identification of bio industrial bio-based value systems for project analysis*.

The aim of the circularity indicators assessment was to apply the measurement framework to those **twelve products**, detailed in **Table 1**. Subtle nuances are, however, detailed in section 2.3.1.

Table 1*: BIORADAR's target bio-based products.*

Fertiliser	Packaging	Textile
Algae biomass	Cardboard	Bio-nylon*
Compost	Paper	Hemp fibre
Feather meal	Bio-polyethylene (Bio-PE)*	Lyocell
Wood vinegar	Polyethylene furanoate (PEF)*	Wool

* Suitable data for applying the circularity assessment to these products was not available. A more detailed explanation can be found in section 2.3.1.

The goal of this report is to **offer a clear view of the advantages and disadvantages of currently available product circularity indicators** used in bio-based industries, as well as **proposing a measuring framework** to be used by businesses engaging in the production of such products.

1.2 WORK PACKAGES AND TASKS RELATED WITH THE DELIVERABLE

This deliverable refers to **Task 2.2** "Evaluation of existing metrics on circularity for industrial bio-based systems and use-cases and proposition of new indicators" and **Task 2.3** "Coupling of indicators among methodologies" included in **WP2** "Identifying and assessing circularity aspects of industrial bio-based systems and embedding them into BTI framework".

Results of **product circularity indicators are to be transferred to WP3** to be incorporated in **BIORADAR's digital monitoring tool**, and the methods followed and key findings are to be transferred to **WP4 to be showcased in BIORADAR's replication facility**.

2. MATERIALS AND METHODS

2.1 EVALUATION OF EXISTING INDICATORS

The evaluation of indicators began in D2.1 – *Report on identification of circularity indicators methodologies for industrial bio-based systems*, with the assignment of tags to each identified indicator. **Table 2** details which **tags (attributes)** were assigned to each one of the selected indicators, based on **whether do they capture those aspects within its formulas or calculation methods**.

Table 2: *Characterisation tags assigned to each indicator during selection stage.*

Indicator (Source)	Tags
Circular index (Enel, 2018)	Energy, Internal loops, Product lifetime, Recyclability, Recycled input, Relative value, Waste, Water consumption.
Circularity indicator of nutrient (Cobo et al., 2019)	Efficiency, Relative value.
Recycling effectiveness (Roithner & Rechberger, 2020)	Efficiency, Entropy, Relative value.
Resource pressure (Desing et al., 2021)	Efficiency, Product lifetime, Relative value.

Once the attributes for each indicator were identified, their gaps became also evident. A detailed analysis of the **gaps identified can be found in *D2.1 – Report on identification of circularity indicators methodologies for industrial bio-based systems*. Below, the gaps considered key for each indicator are specified**.

2.1.1 Circular index

As a result of the analysis conducted in D2.1 – *Report on identification of circularity indicators methodologies for industrial bio-based systems*, circular Enel's (2018) circular index was selected because of its holistic approach to the circularity of products which considers plenty of cases and aspects, from material sourcing, recycling potential, (renewable) energy use, end of life, and other circular activities such as sharing, repairing, and product-as-a-service business models.

Under the "CirculAbility model", Enel (2018), developed the circular index methodology, **focused on material and energy consumption**. Some years after, they launched their "Economic CirculAbility" during the World Economic Forum 2023 in Davos, which compares the group's EBITDA with the amount of resources consumed through the value chain (Enel, 2023).

Enel's circular index was found to be **quite comprehensive**, considering a big number of attributes relevant to product circularity, and doing so in a less complex way than, for example, the Ellen McArthur Foundation's Material Circularity Indicator (Ellen McArthur Foundation & ANSYS Granta, 2019).

It takes into account product useful lifetime, the nature of material inputs (i.e., virgin, renewable/non-renewable, recycled/reused), of material outputs (i.e., to recycling, to reuse, to waste), recycling taking place within product manufacturing, and the nature of energy inputs (i.e., renewable/non-renewable, reused or recycled). It even considers variables that were considered not to be applicable to BIORADAR target bio-based products, such as reusing, sharing and repairing.

Nevertheless, it **fell short when highlighting the biological cycle**. Being a comprehensive and conglomerated indicator has the **downside of diluting relevant information into a single score**. **Enel's Circular Index was not developed specifically for bio-based products but rather for electric equipment**. It was found to actually be applicable to any type of product, which makes it a **great option for comparing among sectors, but at the expense of failing to capture some key aspects and nuances**.

To use it for bio-based products, and with the available information, some methodological adaptations were needed, and are described below.

Equation 1 comprises the main formula for calculating circular index (CI). It is composed of two terms: (1) the circular flow (Cf), which considers the contribution in terms of circular inputs and outputs of material and energy, ranged between 0 (linear product) and 1 (ideal circular product); and (2) a fraction composed by the "non-circular contribution" from energy and materials (1-Cf) multiplied by a use factor (Cu-1/2*Cu) that considers the load factor of the "non-circular contribution", ranging between 0 and 0.5.

The term Cf can then be taken as the measurement of the circularity in the flows of material and energy, and Cu as the measurement of the circularity in the use approach.

Equation 1*: Circular Index calculation formula.*

$$CI = Cf + \frac{(1 - Cf) \times (Cu - 1)}{2 \times Cu}$$

Equation 2 and **Equation 3** show how to calculate Cu and Cf, respectively. Cu, being the measurement of the circularity in the use considers three aspects:

- Extended lifetime of the product (L_{ex}) compared to the business-as-usual lifetime of the product (L_{BAU}). The extended lifetime makes reference to the effect of activities such as repairing, refurbishing or remanufacturing, that may prolong the time the product is used.

- The time the product is used on a sharing scheme (U_{sh}) compared to the time it is used on a business-as-usual scheme (U_{BAU}).

- The time the product is used on a product-as-a-service scheme (U_{PAS}) compared to the time it is used on a business-as-usual scheme (U_{BAU}).

Equation 2*: Circular use calculation formula.*

$$Cu = \frac{L_{ex}}{L_{BAU}} \times \frac{U_{sh}}{U_{BAU}} \times \frac{U_{PAS}}{U_{BAU}}$$

Given the nature of the target sectors, sharing and product-as-service (PAS) scenario were neglected. However, **assigning directly 0 to U_{sh} and U_{PAS} would cause the entire value of Cu = 0**, causing an indeterminacy in **Equation 1**. For this reason, **U_{sh}, U_{PAS} and U_{BAU} were fixed to 1**. From a theoretical standpoint, this would be equivalent to saying that the products are used 100% both under sharing and PAS scheme, or just excluding them from the analysis and reducing Cu only to L_{ex}/L_{BAU}. **For fertilisers**, anyway, there is no lifetime extension possible once they are applied on soil, so for that sector, **Cu is fixed to 1** (which, again, would theoretically represent a 100% circular use).

Equation 3*: Circular flow calculation formula.*

$$Cf = \frac{2 - \left(\frac{V}{Ti} + \frac{W}{To}\right)}{2}$$

where
V is the amount of virgin materials coming from non-renewable sources (kg),
Ti is the total mass of inputs (kg),
W is the total mass of materials sent to landfill/incineration/waste treatment (kg), and
To is total mass of outputs (kg).

Regarding Cf, no major adaptations were needed. Its components were calculated following Enel's (2018) methodology, as detailed in **Equation 4** to **Equation 6**.

Equation 4*: Total inputs calculation formula.*

$$Ti = RC_i^n + RU_i + RES + V$$

where
RC_i^n is the amount of recycled material used in manufacturing (kg),
RU_i is the amount of reused[1] material used in manufacturing (kg), and
RES is the amount of virgin materials coming from renewable sources (kg).

Equation 5*: Total outputs calculation formula.*

$$To = RC_o^n + RU_o + O + W$$

where
RC_o^n is the amount of materials sent to recycling after the manufacturing process (kg),

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[1] Here, reused material refers to those not going through any reconditioning process, thus used directly after its first life without treating or modifying it.

RU_o is the amount of materials to be reused after the manufacturing process (kg), and
O is the mass of the final product, also referred to as the reference unit (kg).

Equation 6*: Total output sent to disposal calculation formula.*

$$W = WRC_i + WRC_o + W_o$$

where
WRC_i and WRC_o are considered a single value representing the waste generated during recycling processes that happen during the manufacturing, treating process residues (kg), and
W_o is the amount of materials sent to landfill/incineration after the manufacturing process (kg).

To include energy consumptions, RES, RU_i, V and RC_i are modified by adding an energy amount, converted to material weight.

To do so, **Enel's (2018) conversion factor for electrical energy is used**. That factor follows the logic of *"representing the amount of energy in terms of the amount of materials used to generate such energy according to the used sources"*.

To do so, electricity generation matrices per country or regions function as the base for the calculation. Electricity generation data used in this report is detailed in **Table 3**.

Table 3*: Electricity generation matrices for the national grids of the studied products. Sources: (a) International Energy Agency (2023), and (b) European Council (2024).*

Energy source	Italy's generation (GWh)[a]	Poland's generation (GWh) [a]	Estonia's generation (GWh) [a]	EU-27's generation (GWh) [b]
Wind	23,303.00	23,249.00	683.00	419,919.00
Solar PV	30,711.00	11,344.00	629.00	200,716.00
Geothermal	5,692.00	-	-	5,282.00
Biomass	18,405.00	8,519.00	1,768.00	116,204.00
Hydro	41,999.00	3,733.00	23.00	298,433.00
Nuclear	-	-	-	578,379.00
Thermal:	144,161.00	119,501.00	2,570.00	1,022,067.00
Coal	14,376.00	100,293.00	2,530.00	417,278.00
Natural gas	118,981.00	16,983.00	22.00	517,636.00

Energy source	Italy's generation (GWh)[a]	Poland's generation (GWh) [a]	Estonia's generation (GWh) [a]	EU-27's generation (GWh) [b]
Petroleum products	10,191.00	2,225.00	18.00	42,256.00
Other fuels	613.00	-		44,897.00
TOTAL	**264,271.00**	**166,346.00**	**5,673.00**	**2,641,000.00**

To transform those energy values in amount of materials, the quantity of resources needed to generate that energy is incorporated in the equation. **Enel's (2018) assumption that "the amount of used material to generate renewable energy" is zero was followed**. For the other energy sources, the resource consumption rates detailed in **Table 4** were used.

***Table 4**: Gross calorific values of the fuels of interest for the conversion factor for electrical energy.*

Fuel	Gross calorific value (GWh/kg)	Used for	Source
Coal	6.67×10^{-6}	Coal	Eurostat (2014)
Natural gas	1.54×10^{-6}	Natural gas	The Engineering Toolbox (2003)
Uranium (Yield)	0.43	Nuclear	Foro nuclear (n.d.)
Petroleum naphtha	1.34×10^{-5}	Petroleum products	The Engineering Toolbox (2003)
Heavy fuel oil	1.16×10^{-5}	Other fuels	The Engineering Toolbox (2003)

Then, the material requirement for each energy source (assuming 100% efficiency) was obtained by dividing the energy output from each of the non-renewable sources by the corresponding gross calorific value or yield. Finally, the conversion factor for electrical energy was the result of dividing the material requirement by the energy output, resulting in a value with units kg/kWh that, when multiplied by the energy consumptions of each system, results in a mass value (kg).

These mass values were named RES_Ener (renewable energy consumed in manufacturing), RU_i_Ener (energy consumption coming from the energy valorisation of a material, for instance, by producing biogas through anaerobic digestion), V_Ener (non-renewable energy consumed in manufacturing), and RC_i_Ener (energy consumption coming from the recovery of another energy stream, for instance, surplus steam that is converted into electricity through turbines).

Ultimately, the RES, RU_i, V and RC_i values to be used in **Equation 4** were the sum of the original (material) value and the energy-based value.

The final result is then a circular index ranging between 0 and 1, conveying an aggregation of all the circularity aspects considered during its

calculation, being 0 a fully linear product, and 1 an ideal fully circular product.

2.1.2 Circularity indicator of nutrient

For measuring **circularity of fertilisers**, the indicator selected was the one proposed by Cobo et al. (2019), which is aligned with the common practice found for fertilisers: **a yield indicator of how much of a nutrient in the input is recovered and ultimately contained in the finished fertiliser**.

They did so for a multi-stream system which may have different recovery efficiencies. They even included in the equation the efficiency of a crop (i.e., corn) in absorbing the target nutrient. However, **focusing so much on yield causes to leave out of the assessment other aspects** that may also be relevant to circularity. One such aspect is related to the circular economy **principle of slowing resource loops** (Kirchherr et al., 2023). Slowing resource loops is paramount in agriculture and soil management, particularly regarding application of nutrients to soil and the efforts towards developing slow-release fertilisers that prevent higher eutrophication risks.

Cobo et al.'s (2019) original approach is detailed in **Equation 7**.

***Equation 7**: Circularity indicator of nutrient calculation formula.*

$$CI_i(x.y) = \frac{\sum_{k=1}^{m}\sum_{j=1}^{n} R_{ijk}(x,y)\cdot\eta_{rij}\cdot\eta_{pik}}{W_i}$$

where
CI_i is the circularity indicator of nutrient i,
W_i is the amount of nutrient i present in the collected waste (kg),
R_{ijk} is the amount of nutrient i that enters the recycling unit process j, and the subsequently recovered nutrient i that enters the corn production unit process k (kg),
η_{rij} is the recycling efficiency of the recycling unit process j for nutrient i (kg of recovered nutrient i per kg of nutrient i that enters the unit process j), and
η_{pik} is the efficiency of the corn production unit process k at taking up the recovered nutrient i (kg of nutrient i taken up per kg of nutrient i entering the process k).

For the specific application within BIORADAR project, the Circularity Indicator of Nutrient (CIN) was simplified, and its scope limited to the application of fertiliser to soil; in other words, the crop nutrient absorption was excluded. The resulting indicator, nevertheless, **still captures the essence of what Cobo et al. (2019) aimed for: the efficiency of the fertiliser production process on keeping as much input nutrient as possible in the finished product**. To calculate it, **Equation 8** was used.

***Equation 8**: Simplified Circularity Indicator of Nutrient calculation formula.*

$$CI_i = \frac{R_i \cdot \eta_i}{W_i}$$

where
R_i is the amount of nutrient i that enters the recycling process (kg),
η_i is the efficiency of the recycling process on recovering the nutrient i (%), and
W_i is amount of nutrient i in the collected waste (kg).

By expressing the formula in that way, there is intrinsic the sense that the collected nutrient may undergo an intermediate process before entering the actual fertilizer manufacturing process where a certain amount of nutrient may be lost. This loss of nutrient in intermediate stages is the difference between R_i and W_i. So, the simplified CIN accounts for the circularity of the entire process, and not only the fertiliser manufacturing *sensu stricto*.

For example, if food waste is collected to be composted, before the composting starts some grinding or improper materials separation may be carried out. If, during these processes, some nutrients are lost, this will affect the CIN of that specific compost.

2.1.3 Recycling effectiveness

For measuring circularity of **packaging materials**, Roithner & Rechberger's (2020) indicator was chosen, which is based on the concept of **statistical entropy**. This concept was developed by Rechberger & Brunner (2002) and it basically quantifies **the potential of a system to concentrate or dilute substances**.

The authors emphasise the difference between thermodynamic entropy (S, J/mol*K) and statistical entropy. Even though they are “formally identical”, there is no physical relationship between these two terms.

What statistical entropy contributes to the indicator is the sense of material quality. When dealing with **recycling processes, attention should be paid to losses of quality degradation that materials undergo**, and Recycling effectiveness (RE) indicator conveys that in a more manageable way.

By focusing all the measurement on the recycling loop, **other aspects may be overlooked** under this approach. **For example, the reduction of virgin material consumption** or even the reusability are left out the measurement.

The formula used to calculate RE is detailed in **Equation 9,** and its terms are further detailed in **Equation 10** to **Equation 15**.

***Equation 9**: Recycling effectiveness calculation formula.*

$$RE = 1 - H_{out,rel}$$

where
RE is the recycling effectiveness, ranging from 0 to 1, 1 being the best recycling performance possible, and
$H_{out,rel}$ is the relative statistical entropy.

To calculate the relative statistical entropy, following **Equation 10** to **Equation 15** is needed.

Equation 10*: Relative statistical entropy calculation formula.*

$$H_{out,rel} = \frac{H_{out}}{H_{max}}$$

where
H_{out} is the statistical entropy, and
H_{max} is the maximum statistical entropy.

From this point on, formulas are referenced to a system with one input flow (inp), and different output flows (i=index for output flows). These output flows have different concentrations of the target material.

Equation 11*: Statistical entropy calculation formula.*

$$H_{out} = -\sum_{i=1}^{k} m_{out,i} \cdot c_{out,i} \cdot \log_2(c_{out,i})$$

where
$m_{out,i}$ is the specific mass fraction of target material in the output stream i (e.g., kg plastic per kg PET input), and
$c_{out,i}$ is the concentration of the target material in the output flow i (%).

Equation 12*: Specific mass fraction of target material in output i calculation formula.*

$$m_{out,i} = \frac{M_{out,i}}{X_{inp}}$$

where
$M_{out,i}$ is the total output mass flow of stream i, and
X_{inp} is the total input mass flow of target material.

Equation 13*: Concentration of the target material in output i calculation formula.*

$$c_{out,i} = \frac{X_{out,i}}{M_{out,i}}$$

where
$X_{out,i}$ is the output mass flow i of the target material.

Equation 14: *Maximum statistical entropy calculation formula.*

$$H_{max} = \log_2(m_{inp})$$

where

m_{inp} is the specific mass fraction of target material in the input stream.

Equation 15: *Specific mass fraction of target material in input stream.*

$$m_{inp} = \frac{M_{inp}}{X_{inp}}$$

where

M_{inp} is the input mass flow.

To better understand the system modelled, **Figure 1** details the variables making reference to the total mass balance (M), and the variables making reference to the target material mass balance (X).

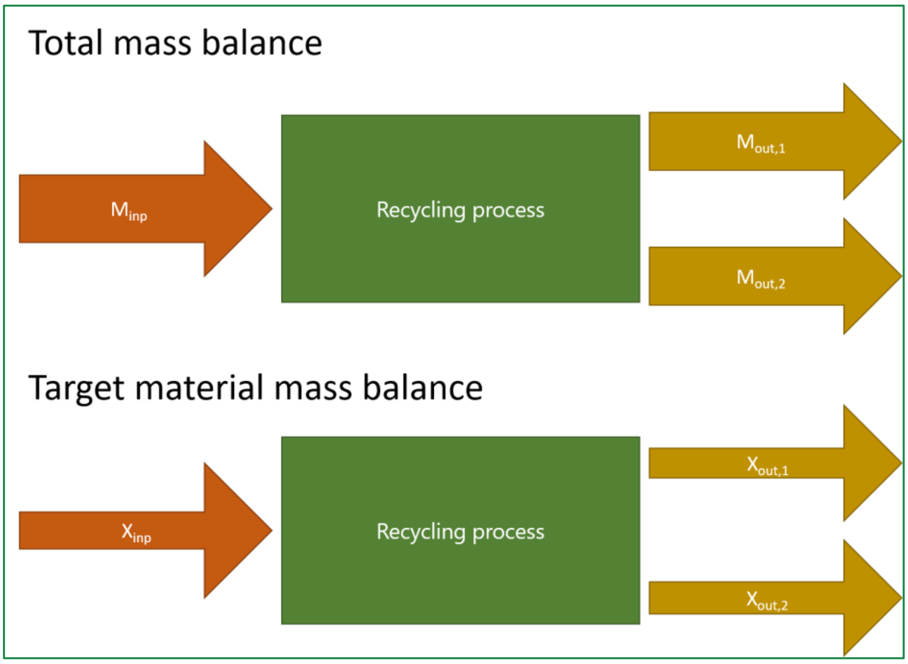

Figure 1: *Diagram for a recycling process that transforms the input mass flow (left side) into two output mass flows (right side). Adapted from: Roithner & Rechberger (2020).*

Therefore, the RE indicator can be calculated leveraging on the global and component-wise mass balances.

2.1.4 Resource pressure

For the textile products, **Resource pressure (RP)** was selected. It is a circular design indicator developed by Desing et al. (2021), following the results obtained by Desing et al. (2020a) and Desing et al. (2020b) which is calculated out of six design parameters: **mass in product, product lifetime, manufacturing losses, primary material content, recyclability and cascadability**.

It merges those six design parameters with **ecological resource potential (ERP)**, a variable proposed by Desing et al. (2020b) as a way to convey the "maximum theoretical potential for producing one material within Earth system boundaries, when no other anthropogenic activity would take place".

Introducing the **concept of planet boundaries is perhaps the biggest value added by this indicator**. On the other hand, by focusing on the entire fibre production process **it may not shed enough light on worrisome stages** like, for example, **fibre treatments** required to rend them ready to be used by the consumers, and that may require significant amounts of polluting substances.

The RP calculation method is detailed in **Equation 16** to **Equation 23**.

Equation 16*: Resource pressure calculation formula.*

$$\tau = \frac{1}{2}\frac{m_{product}}{ERB}\frac{1}{t_L}(1+\gamma_m)(1+\alpha-\eta_r-\eta_c)$$

where
τ is the resource pressure,
$m_{product}$ is the mass flow of primary material required (kg),
ERB is the ecological resource budget,
t_L is the product lifetime (years),
γ_m is the manufacturing losses,
α is the primary material mass fraction,
η_r is the recyclability, and
η_c is the cascadability.

Equation 17*: Manufacturing losses calculation formula.*

$$\gamma_m = \frac{m_{lost}}{m_{product}}$$

where
m_{lost} is the mass of primary material that is lost during manufacturing (kg).

Equation 18*: Primary material mass fraction calculation formula.*

$$\alpha = \frac{\dot{m}_{prim}}{\dot{m}_{product}}$$

where
$\dot{m}_{prim}$ is the flow of primary material (kg/year), and
$\dot{m}_{product}$ is the material flow required by the product (kg/year).

Equation 19*: Recyclability calculation formula.*

$$\eta_r = \frac{\dot{m}_r}{\dot{m}_{product}}$$

where
$\dot{m}_r$ is the recycled material flow, i.e., material that can be recovered to be used as an input to produce the same product again, at least hypothetically (kg/year).

Equation 20: *Cascadability calculation formula.*

$$\eta_c = \frac{\dot{m}_c}{\dot{m}_{product}}$$

where
$\dot{m}_C$ is the cascaded mass flow, i.e., material that can be used as an input in another and lower (quality) function (kg/year).

Equation 21: *Mass flow required for the production of a product calculation formula.*

$$\dot{m}_{product} = \frac{m_{product}}{t_L}(1+\gamma_m)$$

Desing et al. (2021) also present **Equation 22**, that represents the mass balance for one material in the product system.

Equation 22: *Mass balance for one material in the production system.*

$$\dot{m}_{product} = \dot{m}_{prim} + \dot{m}_s + \dot{m}_r = \dot{m}_{loss} + \dot{m}_c + \dot{m}_r$$

where
$\dot{m}_S$ is the secondary materials flow, i.e., materials cascaded from another system with higher quality (kg/year).

The only missing term of the equation is the ecological resource budget (ERB). Desing et al. (2021) propose using the ecological resource potential (ERP) instead, for design guidance, “which is based on the material’s impact intensity alone”. Its calculation procedure is detailed by Desing et al. (2020b) and is briefly explained below.

First of all, a definition of Earth system boundaries (ESB) in a unit that can be measured with Life Cycle Assessment (LCA) is needed. The ESB considered by Desing et al. (2020b) are:

- Climate change: direct fossil CO_2 emissions to air.
- Climate change: global warming potential (GWP) for a time horizon of 100 years.
- Biosphere integrity: potentially disappeared species.
- Stratospheric ozone depletion: emission of O_3 depleting substances (ODS)
- Biogeochemical flows: P to oceans.
- Biogeochemical flows: P to soil.
- Biogeochemical flows: industrial and intentional biological fixation of N.
- Land system change: appropriable land area.
- Land system change: appropriable land area for cropland.
- Freshwater use: blue water consumption.
- Energy: appropriable technical potential for renewable energy resources in electricity equivalents.

The boundaries need to be specified with an uncertainty range. To do so, Desing et al. (2020a) published "translated boundaries" for those ESB, which were harnessed for this aim, as detailed in **Table 5**. Each ESB has a statistical distribution, based on how its uncertainty range is characterised.

Table 5*: Translated earth system boundaries used in ERP calculation. Source: Desing et al. (2020a)*

Translated control variable	Min.	Max.	Mean	Standard deviation	Distribution	Units
Direct fossil CO_2 emissions to air	$8.25x10^{11}$	$2.20x10^{12}$	-	-	Uniform	kg CO_2/year
Global warming potential	$2.83x10^{12}$	$1.64x10^{13}$	-	-	Uniform	kg CO_2 eq/year
Potentially disappeared species	$1.95x10^{5}$	$1.37x10^{6}$	-	-	Uniform	PDF
Emission of O_3-depleting substances	$4.24x10^{8}$	$3.69x10^{9}$	-	-	Uniform	kg CFC-11 eq/year
P to oceans	$1.10x10^{10}$	$1.00x10^{11}$	-	-	Uniform	kg P ocean/year
P to soil	$6.20x10^{9}$	$1.12x10^{10}$	-	-	Uniform	kg P soil/year
Reactive N emissions	$6.20x10^{10}$	$8.20x10^{10}$	-	-	Uniform	kg N/year
Appropriable land area (all biomes)	-	-	$6.01x10^{13}$	$9.20x10^{12}$	Normal	m^2/year
Appropriable land area for cropland	$1.94x10^{13}$	$2.61x10^{13}$	-	-	Uniform	m^2/year
Blue water consumption	$4.00x10^{12}$	$6.00x10^{12}$	-	-	Uniform	m^3/year
Appropriable technical potential (ATP) for renewable energy resources (in electricity equivalents)	$7.10x10^{13}$	$2.76x10^{14}$	$1.52x10^{14}$	-	Triangular	W

As a second step, ERP calculation needs unit impacts (UI) for the production of one unit of each material. These impacts have to be reported in the same units as the corresponding boundary and include an uncertainty distribution of the impact. To do so, LCA were conducted for the target materials and results were obtained for three different methodologies, namely Product Environmental Footprint 3.0, ReCiPe Midpoint (H) v1.12 / Europe Recipe H, and TRACI 2.1 v1.02 / US-Canadian 2008.

The unit impacts used were those identified by Desing et al. (2020a):

- Inventory result for fossil CO_2 emissions to air.
- GWP indicators.
- Emissions of ODS expressed in CDC-11 eq.
- Inventory results for P and PO_4 emissions to oceans and soil.
- Inventory results for reactive N emissions.
- Inventory results for land occupation.
- Inventory results cropland occupation.
- Inventory results for water emissions to air (evaporative consumption).
- Inventory results for energy carrier flows converted to electric energy.

The third step of ERP calculation is the definition of a probability of violation (p_v), which was set to 0.01, following the procedure conducted by Desing et al. (2020b).

Finally, following Desing et al.'s (2020b) methodology, random values were picked 5,000 times for both the UI and ESB from among each specified uncertainty range. Then, ERP is calculated as the ratio between the $p_{v/2}$-quantile of the ESB distribution (or its lower quantile) and the $(1 - p_{v/2})$-quantile of the UI distribution (or its upper quantile).

The goal is to identify whether the UI's higher quantile surpasses the ESB's lower quantile. This is done for each pair (k) of ESB/UI following **Equation 23**, and arranged in an ERP vector.

***Equation 23**: ERP calculation formula.*

$$ERP_1 = \frac{ESB_k|_{p_{v/2}}}{UI_k|_{1-p_{v/2}}}$$

The smallest value contained in the ERP vector would be the ERP for the material and the respective limiting boundary. And that would be the value used in **Equation 16** as ERB for obtaining the resource pressure indicator.

2.2 PROPOSITION OF NEW INDICATORS

With the aim of complementing the selected indicators, **one accompanying metric was proposed for each one of the indicators described in the previous section**. Their development was guided by the gaps identified in the assessment, and summarized in **Table 6**. It is not a comprehensive gap list, rather the identification of **gaps that could be bridged within the scope of the BIORADAR project**.

***Table 6**: Identified gaps of selected indicators.*

Indicator	Identified gaps
Circular Index	- No direct comparison to the linear counterpart. - Not accounting for biodegradable/compostable content.
Circularity Indicator of Nutrient	- Not accounting for nutrient release speed. - Not accounting for waste generation during the manufacturing process.
Recycling Effectiveness	- Not accounting for energy consumption. - Not accounting for waste ultimately generated at the end of life. - Not considering the ratio of bio-based materials to total product weight.
Resource pressure	- Not considering energy consumption during production process. - Not considering mass of non-renewable waste generated. - Not considering biodegradability of the material. - Not considering synthetic-substances-intensive stages such as fibre treatment.

With this map in mind, four new indicators were built. Each one of them aims to address one of the identified gaps.

2.2.1 Biodegradable/compostable content

To complement the Circular Index, **the gap to be bridged was precisely the lack of accounting for biodegradable/compostable content**. It was done in a straightforward fashion, by formulating a ratio equation (**Equation 24**).

***Equation 24**: Biodegradable/compostable content calculation formula.*

$$BC = \frac{Bm}{Tm}$$

where
BC is the biodegradable content,
Bm is the mass of biodegradable materials used in manufacturing (kg), and
Tm is the total mass of the product (kg).

Its aim is to shed light on **how much of the product is obtained from biodegradable/compostable materials** when being used alongside the Circular Index, which gives a sense of the overall circularity of the material and its production process.

The difference between biodegradability and compostability is not a minor concept here. Flachenecker (2024) outlined the main difference, based on the EU policy framework for biobased, biodegradable, and compostable plastics:

- Bio-based: RED III for land use and biodiversity, for GHG emission more research is needed.
- Biodegradable: only specific applications (e.g., mulch films).
- Compostable: only industrially compostable plastics (e.g., plastic bags for bio-waste, tea and coffee bags).

For packaging materials, for example, the term “compostable” is more used, as it conveys more guarantees of the transformation of the material into an organic substance within a specific time frame.

For fertilisers, for example, the term “compostable” does not add any value. Even less when the assessed product is precisely compost.

As of textiles, there is an ongoing debate. While wide sectors of the industry are focused rather on recyclable fibres, there is a growing number of innovative firms developing biodegradable fibres. The (European Commission, 2024) defines something as biodegradable if the condition that “a biodegradation level of at least 90% must be reached in less than 6 months” is met.

Mehta (2023) classified natural textile polymers (those with some biodegradability potential) into: cellulosic, protein, and mineral. Cellulosic fibres are, for instance, cotton, linen, jute, hemp, flax, sisal, etc. But some other human-made innovative fibres are being classified as biodegradable, such as Tencel™, viscose, soysilk, Polylactic acid (PLA), Polybutylene succinate (PBS), etc. **Table 7** summarises expected degradability of different types of fibres, as reported in previous scientific studies.

Table 7*: Expected textile fibres degradability based on previous studies. Source: (Mehta, 2023)*

Polymer (natural/synthetic/biopolymer)	Percentage degradation	Timeline
Cotton	25 – 100%	25 – 90 days
Wool	43%	After 168 days
Flax	>70%	In 180 days
Nylon	<1% observed	After 270 days
PET	<1% noticed	After 700 days
PLA	60-100%	In 60 – 120 days
PCL	70-100%	In 60 – 100 days
PBAT	30-67%	In 42 – 45 days
PHBH	30-95%	In 25 – 60 days
Ramie	42%	In 168 days

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However, **it is very important to highlight that these values are only referenced to raw fibres.** Commercial textile products usually undergo a series of treatment processes like blending with synthetic fibres, coating with chemicals, or dyeing with colours, which rend the final product not biodegradable at all. This indicator is intended only to the materials, which in the case of textile are the raw fibres. The fibre treatment indicator index (c.f. 2.2.4) sheds light on the other side of the coin: the circularity of fibre treatment processes.

Therefore, both wordings have been kept, making it clear that **“compostable” is used for packaging, and “biodegradable” is used for fertilisers and textiles**.

2.2.2 Nutrient slow release index

For the fertiliser sector, the Circularity Indicator of Nutrient is complemented with a measurement of **how fast does bio-based fertiliser release nutrients, compared to mineral fertilisers**. This is one of the key characteristics of any fertiliser, since the fast release of nutrients may result in crops not being able to timely absorb them and thus being lost through leakage. **Nutrient leakages are one of the main causes of fresh- and groundwater eutrophication**.

Thus, the calculation for nutrient slow-release index is based on **Equation 25**.

Equation 25*: Nutrient slow-release index calculation formula.*

$$NSRI = 1 - \frac{bioNRC_n}{minNRC_n}$$

where
NSRI is the nutrient slow release index,
$bioNRC_n$ is the soil nutrient relative content n days after the application of bio-based fertiliser, and
$minNRC_n$ is the soil nutrient relative content n days after the application of mineral fertiliser.

Both $bioNRC_i$ and $minNRC_i$ have to be measured within the same timeframe. The indicator ranges between 0 and 1, 0 being the case when bio-based and mineral fertilisers have the same release speed (less circular), and tends to 1 when the bio-based fertiliser is significantly slower than the mineral option (more circular).

When proposing this indicator, it should be acknowledged that data availability for soil nutrient relative content is rather scarce, and moreover for innovative and recently-developed products. Notwithstanding, given the relevance of the topic and the expected expansion of this kind of measurements, this indicator is proposed to accompany the Circularity Indicator of Nutrient.

This indicator sheds light on the circular economy **principle of slowing resource loops** (Kirchherr et al., 2023). Slowing resource loops is paramount in agriculture and soil management, particularly regarding application of nutrients to soil and the efforts towards developing slow-release fertilisers that prevent higher eutrophication risks.

Acknowledging that **this information is not always available** for different fertiliser products, **data from Niedziński et al. (2021) was harnessed to obtain a first calculation approach**. **Table 8** details the values to be used when no product-specific data is available. Relative nutrient content makes reference to nutrients present in soil, and the last column “total N content” makes reference to the fertiliser itself.

Table 8*: Nutrient relative content after 35 days for five types of fertilisers, and total N content of each product. Source: Niedziński et al. (2021)*

Type	Fertiliser	(Soil) relative nutrient content (N)		Average	(Fertiliser) total N content (%)
		30% MWHC	60% MWHC		
Bio-based	Turkey manure	0.798	0.681	0.7395	3.86
	Spent mushroom substrate	0.857	0.802	0.8295	2.52
Mineral	UreaPhos (U-PS_c)	0.020	0.014	0.0170	20.81
	UreaPhos (U-PS_f)	0.012	0.011	0.0115	20.89
	Di-ammonium phosphate (DAP)	0.282	0.213	0.2475	18.67

MWHC: (soil) maximum water holding capacity.

2.2.3 Virgin material consumption index

Selected packaging indicator (recycling effectiveness) focuses only on how successful is the recycling process when maintaining material quality. But circular packaging manufacturing entails many other aspects apart from recycling. In particular, **the selected to-be-addressed gap was the consumption of 'linear' materials** (i.e., those not pertaining to circular economy).

To do so, the proportion of virgin materials contained in the product was the selected path, specifically through **Equation 26**.

Equation 26*: Virgin material consumption index calculation formula.*

$$VMCI = 1 - \frac{VM}{TO}$$

where
VCMI is the virgin material consumption index,
VM is the mass of virgin materials (kg), and
TO is the total output mass, or the mass of the final product (kg).

The indicator ranges between 0 and 1, resulting in 0 when the product is totally produced out of virgin materials, and 1 when the product is manufactured entirely from non-virgin materials (i.e., recycled, reused, upgraded, etc.).

2.2.4 Fibre treatment circularity index

For textile, it was identified that, while the manufacturing of bio-based fibres itself may comply with circular principles, in most of the cases the fibre is not directly ready to use and requires further processing. And precisely **during this post-manufacturing treatments, the consumption of non-circular products tends to occur**. Therefore, the path followed was to propose an indicator that may shed light on the post-manufacturing treatment circularity. It is detailed in **Equation 27**.

Equation 27*: Fibre treatment circularity index calculation formula.*

$$FTCI = 1 - \frac{m_{nr}}{m_{fibre}}$$

where
FTCI is the fibre treatment circularity indicator,
m_{nr} is the mass of the non-renewable additives used during treatment, and
m_{fibre} is the mass of the fibre treated.

This indicator allows to quantify the non-renewable resource intensiveness of the post-manufacturing treatment of the fibre, as a relevant aspect when assessing product circularity, not limited to the manufacture of the fibre but also other of its life cycle stages, namely pre-consumer treatments. It ranges from 0 to 1, 0 being a case where the non-renewable additives mass is identical to the treated fibre, and 1 a case where no non-renewable additives are used.

Furthermore, the objective of this indicator is also to bridge the gap identified when presenting the biodegradable/compostable content indicator (c.f. 2.2.1) regarding how **fibre treatment procedures may cause an originally organic or bio-based fibre not to be biodegradable at all, therefore reducing its end-**

of-life circularity options only to the technical cycle, as would be the case with non-bio-based textiles.

2.3 DATA SOURCING

Once the indicators were built, —setting up the circularity measurement framework— the next step was to calculate them for target products. To calculate the indicators, values of each of the required datapoints are required.

Data was obtained from two main sources: available datasets, mostly coming from BIORADAR WP1's environmental life cycle assessments and previous EU-funded projects; and real industry cases.

2.3.1 From available datasets

Data was sourced from life cycle inventories obtained as a result of BIORADAR Work Package 1 activities, other EU-funded projects, and scientific publications, as detailed in **Table 9**.
Life cycle inventories (LCI) are build when conducting a life cycle assessment, taking into consideration all the material and energy flows from and to the studied system. Given its level of disaggregation, all product-circularity-relevant data can be extracted from them.

***Table 9**: Sources of data for calculation of the circularity measurement framework.*

ID	Sector	Product	Description	Data source
1	Fertilisers	Algae biomass	Microalgae from wastewater with CO_2 injection	Castro et al. (2023)
2			Microalgae from wastewater with CO_2 and polyelectrolyte addition	BIORADAR's WP1[2]
3			Microalgae from wastewater with organic flocculant	Arashiro et al. (2018)
4			Microalgae fed with biowaste	BIORADAR's WP1
5		Compost	Food and green waste compost produced in Mediterranean Europe. Energy coming from electricity grid.	FER-PLAY[3]
6			Food and green waste compost produced in Mediterranean Europe. Energy coming from biogas valorisation.	FER-PLAY
7			Food and green waste compost produced in central Europe. Energy coming from electricity grid.	FER-PLAY

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[2] Data referred to as "BIORADAR'2 WP1" was obtained from life cycle assessments conducted within the framework of the project's first work package "Identifying and assessing sustainability aspects (environmental, economic, social) of industrial bio-based systems and embedding them into BTI framework", and whose results will be included in Deliverable 1.2, to be released in June 2025.

[3] FER-PLAY is a project funded under Horizon Europe, that conducted a multi-assessment of alternative fertilisers for promoting local sustainable value chains and clean ecosystems. Website: https://fer-play.eu

ID	Sector	Product	Description	Data source
8			Food and green waste compost produced in central Europe. Energy coming from biogas valorisation.	FER-PLAY
9			Food and green waste compost produced in northern Europe. Energy coming from electricity grid.	FER-PLAY
10			Food and green waste compost produced in northern Europe. Energy coming from biogas valorisation.	FER-PLAY
11		Feather meal	Feather meal production, from unspecified poultry.	BIORADAR's WP1
12			Feather meal production from goose feathers.	BIORADAR's WP1
13			Feather meal production from chicken layer feathers.	BIORADAR's WP1
14		Wood vinegar	Wood vinegar produced valorising wood dust for heat generation, and having non-condensing gases, biochar and bio-crude oil as co-products.	BIORADAR's WP1
15			Wood vinegar produced having non-condensing gases, biochar and bio-crude oil as co-products, and disposing of wood dust as waste.	BIORADAR's WP1
16			Wood vinegar produced valorising wood dust, non-condensing gases, and bio-crude oil for heat generation, and having biochar and surplus bio-crude oil as co-products.	BIORADAR's WP1
17			Wood vinegar produced valorising non-condensing gases and bio-crude oil for heat generation, and having biochar and surplus bio-crude oil as co-products. Wood dust is disposed of as waste.	BIORADAR's WP1
18		Spent mushroom substrate	Spent mushroom substrate produced in Mediterranean Europe.	FER-PLAY
19			Spent mushroom substrate produced in central Europe.	FER-PLAY
20			Spent mushroom substrate produced in northern Europe.	FER-PLAY
21	Packaging	Folding boxboard	SimaPro's dataset[4]: Folding boxboard/chip board {GLO} | market for | Alloc Def, S.	BIORADAR's WP1
22		Corrugated board box	SimaPro's dataset: Corrugated board box {GLO} | market for corrugated board box | Alloc Def, S.	BIORADAR's WP1
23		Kraft paper bleached	SimaPro's dataset: Kraft paper, bleached {GLO} | market for | Alloc Def, S.	BIORADAR's WP1
24		Kraft paper unbleached	SimaPro's dataset: Kraft paper, unbleached {GLO} | market for | Alloc Def, S.	BIORADAR's WP1
26		ToGo Pocket (D1)	Preserve project's demonstrator. Composition: Sr-PLA: 96.56%, protective lacquer: 2.10%, and PVOH coating: 1.34%.	PRESERVE project[5]

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[4] SimaPro is a commercial sustainability software application developed by PRé Sustainability, and is one of the most commonly used software applications to conduct life cycle assessments. Website: https://simapro.com/

[5] PRESERVE is a project funded under Horizon 2020 that developed solutions to improve the recyclability of food packaging. Website: https://www.preserve-h2020.eu/

ID	Sector	Product	Description	Data source
27		Snack Flowpack (D2)	Preserve project's demonstrator. Composition: BioLDPE: 64.94%, PET met: 25.97%, WPI: 5.19%, and wet adhesive: 3.90%.	PRESERVE project
28		Beverage brick (D4)	Preserve project's demonstrator. Composition: Clay-coated board: 80.65%, and PHA coating: 9.68%.	PRESERVE project
29		Molded pulp (D5)	Preserve project's demonstrator. Composition: Molded pulp: 87.24%, and PHA film: 12.76%.	PRESERVE project
30		Blow Molded Bottle (D8)	Preserve project's demonstrator. Composition: Bio r-LDPE: 57.50%, Bio r-HDPE: 30%, Bio r-PET: 10%, and Yparex: 2.50%.	PRESERVE project
31	Textile	Wool	Processes included: antistatic production, polypropylene cone manufacturing, sheep fleece spinning, winding, warping, weaving, finishing and packaging.	BIORADAR's WP1
32		Recycled wool	Processes included: antistatic production, polypropylene cone manufacturing, wool recycling, spinning, winding, warping, weaving, finishing and packaging.	BIORADAR's WP1
33		Jute	Processes included: jute yarn weaving, finishing and packaging.	BIORADAR's WP1
34		Lyocell	Processes included: Lyocell manufacturing[6], weaving, finishing and packaging.	Guo et al. (2021)

The list of products has some differences with that presented in **Table 1**. Three products are missing: bio-polyethylene, polyethylene furanoate, and bio-nylon, one product is substituted: hemp for jute, and six additional products are included: spent mushroom substrate, and five multi-material packaging demonstrators.

The reason for these modifications is that sufficient and reliable **data for bio-polyethylene, polyethylene furanoate, and bio-nylon was not found**, which hindered the respective calculations. Hemp data found was in a format difficult to manage, so it was substituted by another fiber with similar characteristics: **jute**.

On the other hand, a **fifth fertiliser product was included in the assessment (spent mushroom substrate)**. This was done because data needed for nutrient slow release index was only found for that one, and based on it, approximations were done for the four target fertiliser products.

Also, data coming from PRESERVE project was harnessed despite that their products were not previously targeted. It was deemed useful, on the one hand for covering the gap caused by the lack of data for bio-polyethylene, polyethylene

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[6] Lyocell manufacturing: preparation of spinning fluid, premixing and dissolving, treatment before spinning, solvent recovery, anion exchange purification, evaporation of multiple effects, fibre finishing, and drying.

furanoate, and bio-nylon, and on the other hand for expanding the applicability validation of the framework.

2.3.2 From companies

For obtaining primary data, an outreach strategy was put in place. 90 companies were contacted with the aim of validating the measurement framework. Direct contact with them resulted in honing the framework and the concepts used, to match them with those used in the industry.

It also contributed to validating that manufacturing companies indeed have records of the data for calculating the measurement framework, ensuring that the indicators can actually be used by industry actors. Another result of this outreach was the confirmation that circular economy and sustainability are among the worries and goals of manufacturing companies, and most of the contacted ones are already looking for ways to measure and report their sustainability and circularity levels, particularly for carrying out data-based management strategies.

3. RESULTS

Having selected and designed indicators, and sourced the data needed to conduct the calculations, this section presents the results obtained for each of the metrics composing the BIORADAR circularity measurement framework.

3.1 GENERAL INDICATORS

BIORADAR circularity measurement framework is composed by two general indicators (i.e., applicable to any product): circular index, and biodegradable content.

Below, the results of the indicators are presented grouping them by sector. **Figure 2** displays the circular index results for the studied fertilisers, showing the mean value and its standard error.

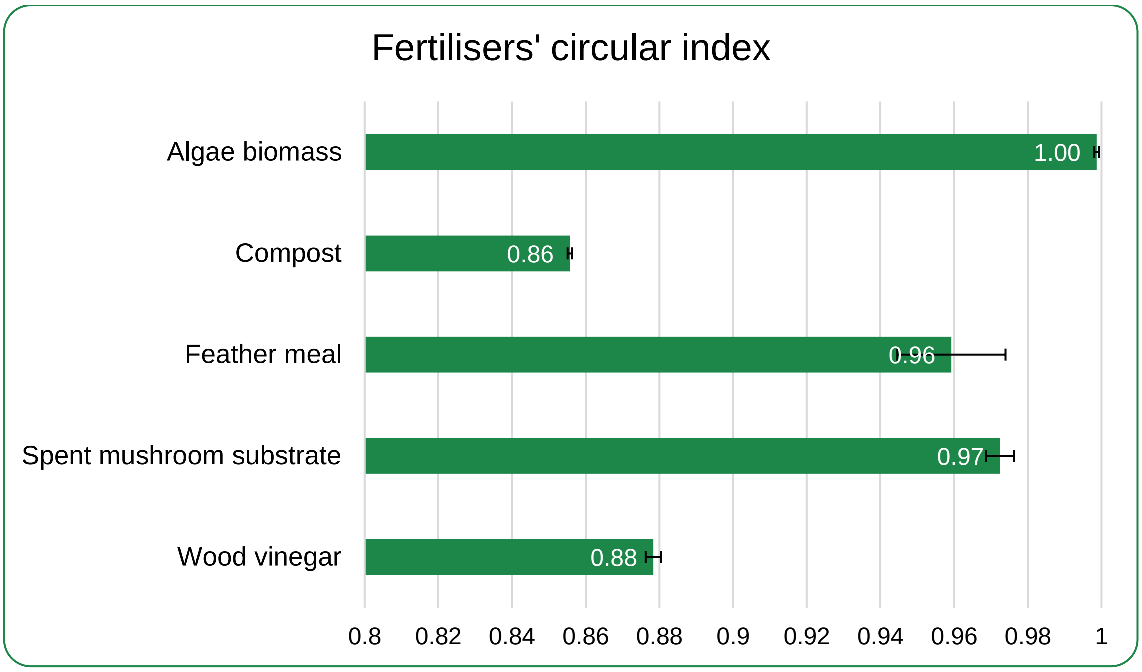

***Figure 2**: Fertilisers' circular index results.*

It is clear that, being all of the studied fertilisers produced from waste flows, its circularity levels are rather high (>0.85).

Analysing the calculation method, and having set the circular use value to 1 (because **neither life extension, sharing nor product as a service are possible in fertilisers**), the **circular index result is equal to the circular factor** value.

The circular factor weighs two aspects: the weight of virgin non-renewable materials in total inputs, and the weight of waste sent to disposal in total outputs. Therefore, **the lower virgin non-renewable materials consumption and waste sent to disposal are, the higher** the circular flow and thus, **the circular index**.

As mentioned in the methodology, **the impact of energy consumption in the calculation is negligible**. As a result, **the reason for the differences** among the five fertilisers studied **are based only on waste generation and virgin non-renewable material consumption**.

Compost had its circular index reduced because of the relatively high amount of waste sent to disposal (28% of outputs, in average). On the other hand, wood vinegar had its circular index reduced because of the high amount of virgin non-renewable material consumption, specifically ethylene glycol —which accounts for 23% of inputs, in average— and is used for avoiding water boiling during condensation (i.e., it is a supply that does not have contact with the product, but is consumed during its manufacturing).

Conversely, spent mushroom substrate and wood vinegar had low rate of waste generation, and low weight of virgin non-renewable materials within total inputs, awarding them near-to-one circular indices.

It is worth noting that algae biomass had the highest circular index among all the fertilisers studied with a value of near-to-one. This is due to the absence of waste generated during its production in most cases studied, since the waste water is sent to be treated and discharged afterwards into the watercourse (Castro et al., 2023). There are some instances where a small amount of waste is produced and is sent to incineration. However, this amount is almost negligible so it does not represent an impact to the circular index (c.f. case of Microalgae fed with biowaste included in **Table 9**).

Hereinafter, packaging's circular index results are presented in **Figure 3**.

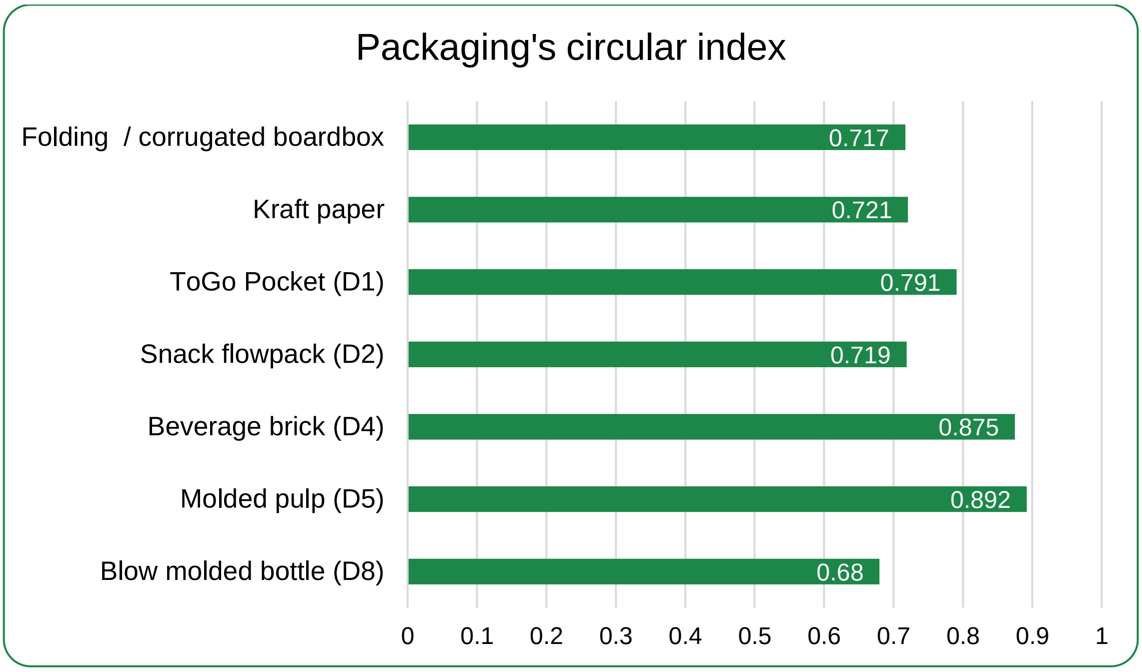

Figure 3: *Packaging's circular index results.*

All the studied packaging products attained a rather high score in the circular index (> 0.68). Both monomaterial products (boardbox and kraft paper) scored very similar (0.72 both, when only considering two decimals), which makes sense given the resemblance of their raw material (cellulose pulp) and manufacturing process.

The lowest score was that of the blow molded bottle, mainly as a result of its higher consumption of non-renewable grid energy compared to the other products. Actually, it consumed ten times more of this kind of energy than molded pulp, and 20 times more than beverage brick, for instance. When managing such a big difference, the energy consumption can indeed affect the circular index calculation.

On top of that, the reason why ToGo Pocket and Snack flowpack got a lower index compared to beverage brick and molded is because during their manufacturing a slightly greater amount of waste is produced, reducing its circularity level.

Accordingly, **Figure 4** depicts the results obtained for textiles when calculating the circular index.

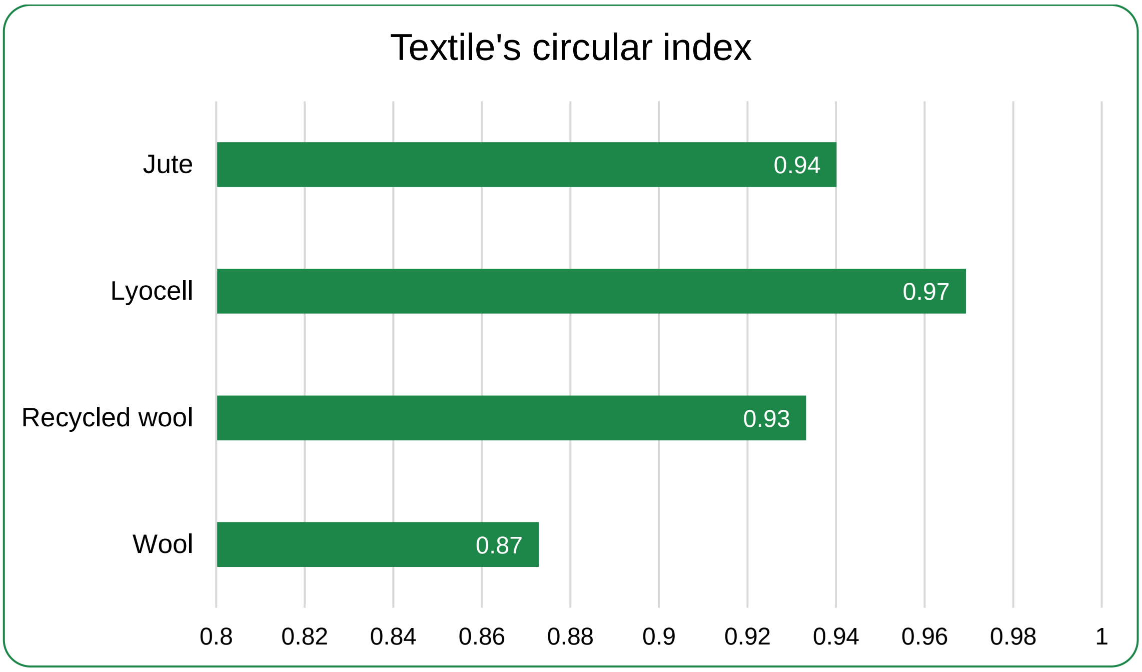

***Figure 4**: Textile's circular index results*

Textile's circular index are higher than 0.86 in the four cases studied. As was done with fertilisers and packaging, the circular use value was set to 1. This is based on the fact that the **product under study was the fibre** and not a specific garment, therefore no life extension was deemed possible. In addition, no sharing or product-as-a-service model were considered. These assumptions also caused the circular index result to be equivalent to the circular factor.

As explained above, the results depend only on two ratios: virgin non-renewable inputs to total inputs, and waste generation to total outputs.

The reason why recycled wool outperforms wool is that, as a result of its higher water consumption (a renewable resource), the ratio virgin non-renewable consumption to total inputs is significantly reduced. This happens while the ratio waste generation to total outputs remains unchanged.

This specific case shows that **circularity indicators may be misleading when assessing extreme cases**, as shown in **Table 10**. Specifically, when the amount of renewable materials is several orders of magnitude bigger than the non-renewable ones. In this case, the renewable material consumed is water, which is a critical resource that should be subjected to appropriate management to reduce its consumption as much as possible. Despite containing recycled content, the amount of water consumption is so high that overshadows it.

Table 10: *Detailed datapoints used for calculating wool and recycled wool circular indices.*

Datapoint	Wool	Recycled wool
Input from renewable resources (RES)	1.134	3,890.004
Input from non-renewable virgin materials (V)	0.064	0.051
Total input (Ti)	1.198	3,890.055
RES/Ti	$5.35\text{x}10^{-2}$	$1.30\text{x}10^{-5}$

The same happens with lyocell and jute, yet in a not-so-extreme way. Lyocell consumes higher amounts of non-renewable materials during its manufacturing, but this gets overshadowed by the amount of water used.

Regarding the second general indicator —biodegradable content—, the results for fertilisers were slightly different, as can be seen in **Figure 5**.

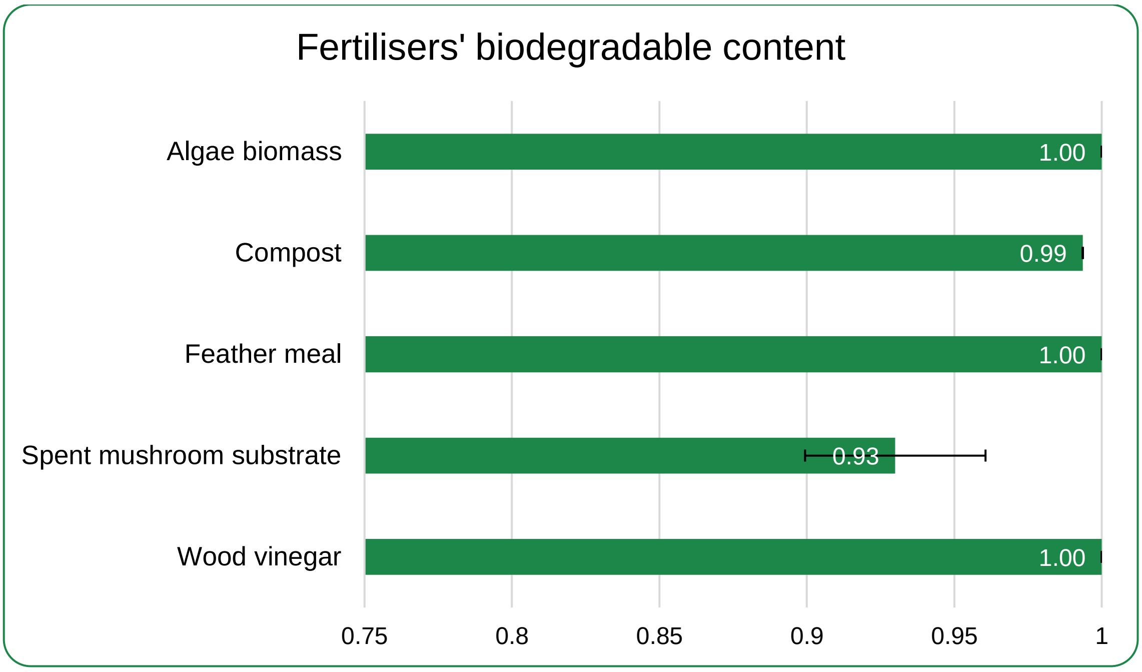

Figure 5: *Fertiliser's biodegradable content results.*

While all of them are still showing higher levels of **biodegradable content** (>0.9), the “outlier” one is spent mushroom substrate. This reflects its content of non-renewable materials such as gypsum and lime, which are added to the substrate mixture to guarantee ideal conditions for the growth of mushrooms, and that remain when the spent substrate is harnessed as a fertiliser. For the other products, they are 100% or almost 100% composed by bio-based materials that once applied to soil are easily degraded by microorganisms and incorporated to the environment.

This indicator helps by **shedding light on the biological materials cycle** which is paramount for circular bioeconomy and commonly overlooked by the circularity indicators mapped so far.

The results of compostable content for packaging products is detailed in **Figure 6**.

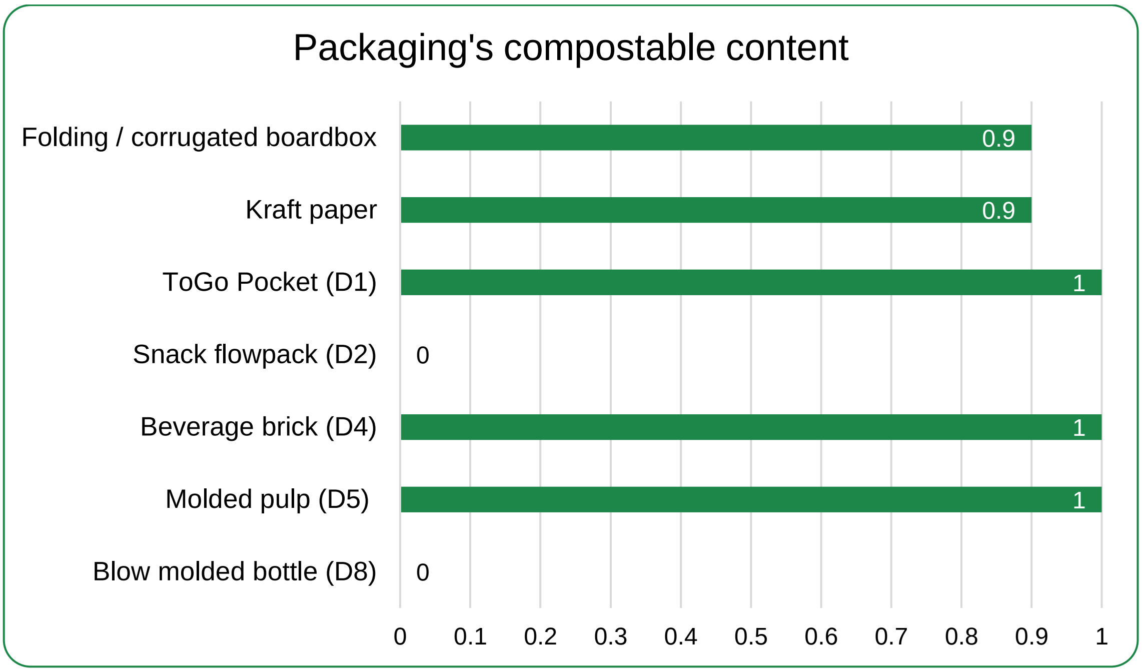

***Figure 6**: Packaging's biodegradable content results.*

As shown in **Figure 6**, the products can be categorized into three groups. The firs of them is composed by products that have 100% compostable content (i.e., ToGo pocket, beverage brick, and molded pulp).

The second group comprises the products scoring 90% compostable content, notably boardbox and kraft paper. This may rise attention as to the components used during the manufacturing that persist even after the core material have been biologically degraded.

The last group is composed by products having 0% compostable content (i.e., snack flowpack and blow molded bottle). This reinforces the notion that bio-based is not a synonym of compostable/biodegradable, and sheds light on the need for these products to improve its end-of-life perspectives.

From the textile side, its results for the biodegradable content indicator are shown in **Figure 7**.

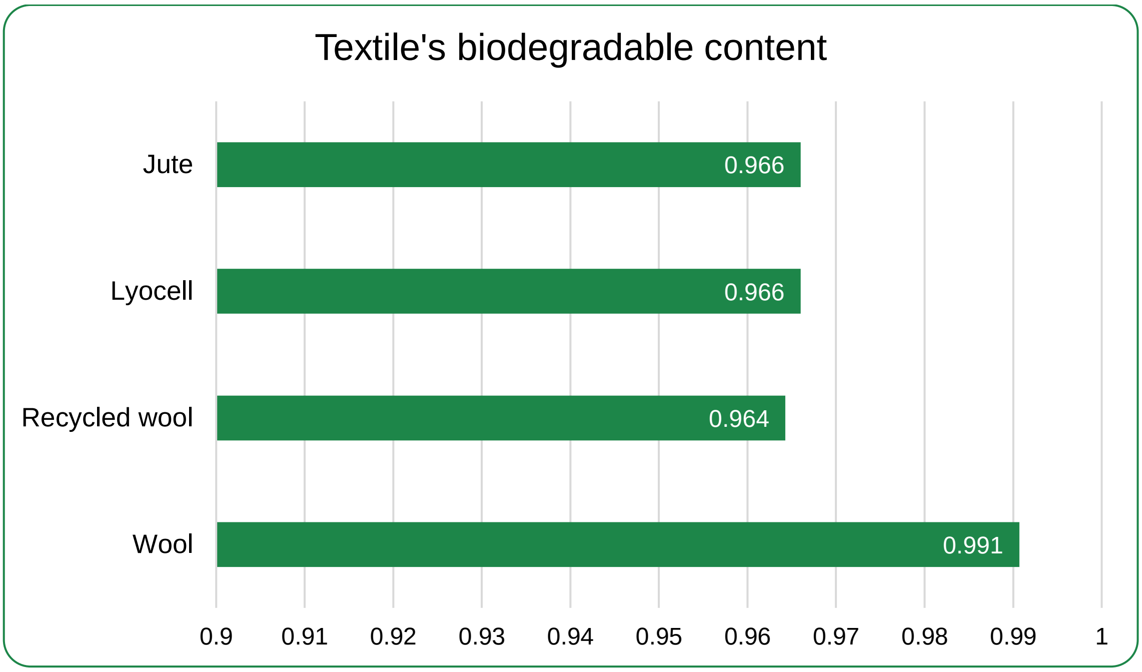

Figure 7*: Textile's biodegradable content results.*

The main variable reflected in the biodegradable content values is the **amount of chemicals that are added to the fibres and that remains within them**. Jute and lyocell, for example, undergo similar finishing processes, thus result in having an almost identical biodegradable content. The difference between wool and its recycled version is because of the amounts of chemicals needed during the recycling stage.

Nevertheless, the differences are rather small (<3%). Given that all the studied fibres share the bio-based characteristic, its differences come mostly from the fibre treatment processes, and the chemical requirements during its transformation.

3.2 FERTILISER INDICATORS

Regarding fertiliser-specific indicators, the BIORADAR circularity measurement framework is comprised by the circularity indicator of nutrient, whose results are presented in **Figure 8**, and the nutrient slow-release index, with its results displayed in **Figure 9**.

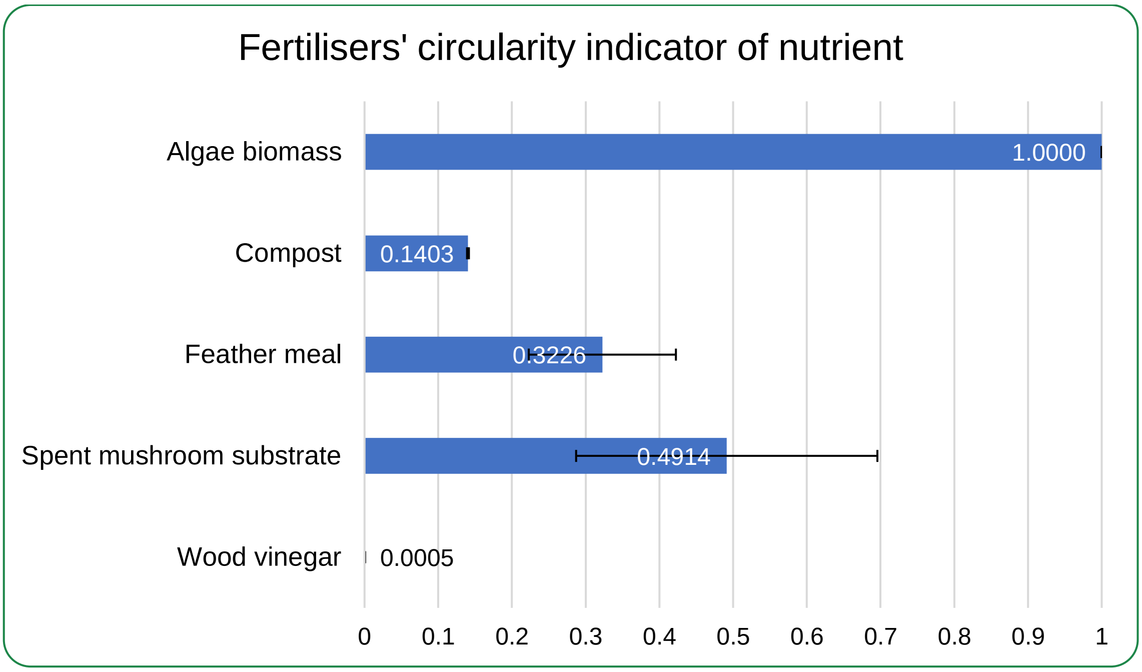

Figure 8*: Fertilisers' circularity indicator of nutrient results.*

The **circularity indicator of nutrient** may be seen as a **process efficiency metric**, putting the focus on nutrient recovery. It basically weights the recovered nutrient as a fraction of the originally available nutrient contained in the waste stream to be treated.

That makes clear that, for example, wood vinegar's circularity indicator of nutrient is 0.0005. The goal of producing wood vinegar is not the recovery of nutrients, but rather the recovery of acetic acid which can be used as a bio-stimulant and bio-pesticide. When analysing the nutrient (nitrogen, in this case), it is originally contained in wood (0.26% w/w); and wood vinegar is the aqueous part of the condensate of the combustion gases produced when burning the wood. This manufacturing process causes that most of the nutrients are actually contained in other co-products (such as biochar, for instance, with 1.46% dry weight), or emitted to air.

On the other hand, spent mushroom substrate may reach a higher value for this indicator thanks to the fact that the waste does not undergo any critical transformation (such as burning), but rather an aerobic decomposition through composting, and the growth of mushrooms which feed themselves with the nutrients contained in the substrate. The variation observed in **Figure 8** reflects the differences caused by different production practices and substrate "recipe mixes".

The fact that algae biomass shows the highest circular indicator of nutrient needs to be considered with caution as, due to the absence of evidence found, it was assumed that its nutrient content was not affected through the different stages of its production (growing and drying).

The latter demonstrates that further research needs to be performed to study the variation of algae nutrient content through the stages of its production in order to verify it these are accurate calculations or if the algae's circular indicator of nutrient may differ.

The **nutrient slow release indices**, as explained in the methodology, has the downside of a **rather small availability of data**. The only targeted fertiliser for which specific data was found is spent mushroom substrate. Turkey manure was the other fertilising product for which relevant data was at disposal. Therefore, the indicator could only be calculated with these values, applying spent mushroom substrate values to itself, compost, and algae biomass, and turkey manure values to feather meal and wood vinegar, as shown in **Figure 9**.

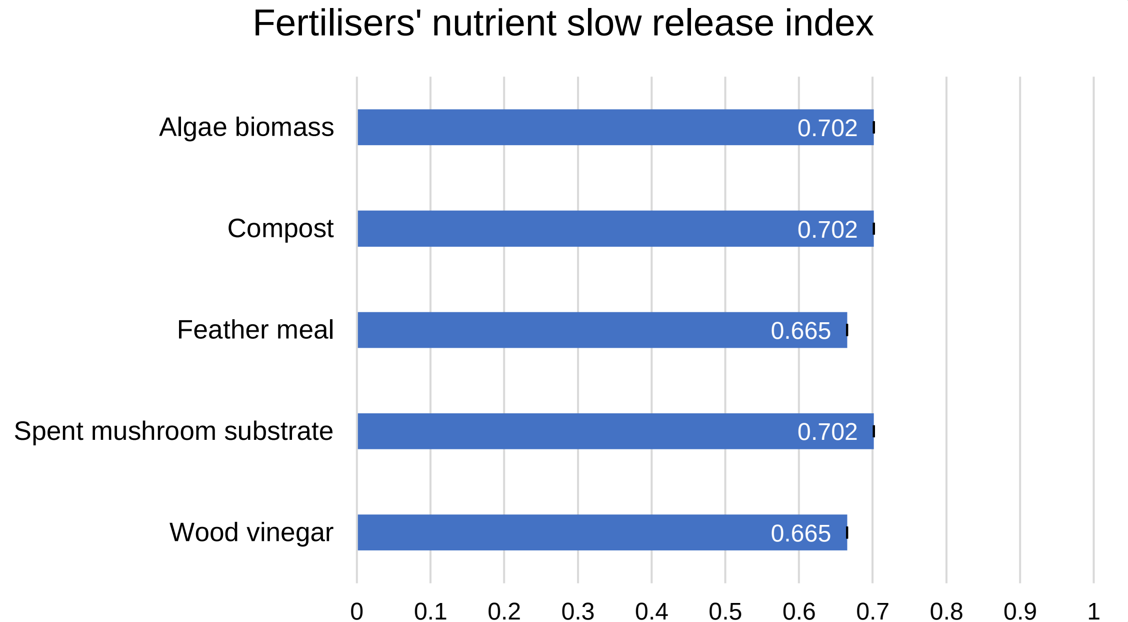

***Figure 9**: Fertilisers' nutrient slow release index results.*

At any rate, the results show the **superiority of bio-based fertilisers when compared to synthetic fertilisers** (c.f., **Table 8**) in regard to nutrient slow release. But this value is highly variable depending on each bio-based-synthetic fertiliser couple being compared. If, for example, a slow-release synthetic fertiliser was taken as counterpart, all the indicator results would decrease.

3.3 PACKAGING INDICATORS

In relation to the packaging indicators, the framework is comprised by the recycling effectiveness, whose results are presented in **Figure 10**, and the virgin material consumption index, with its results displayed in **Figure 11**.

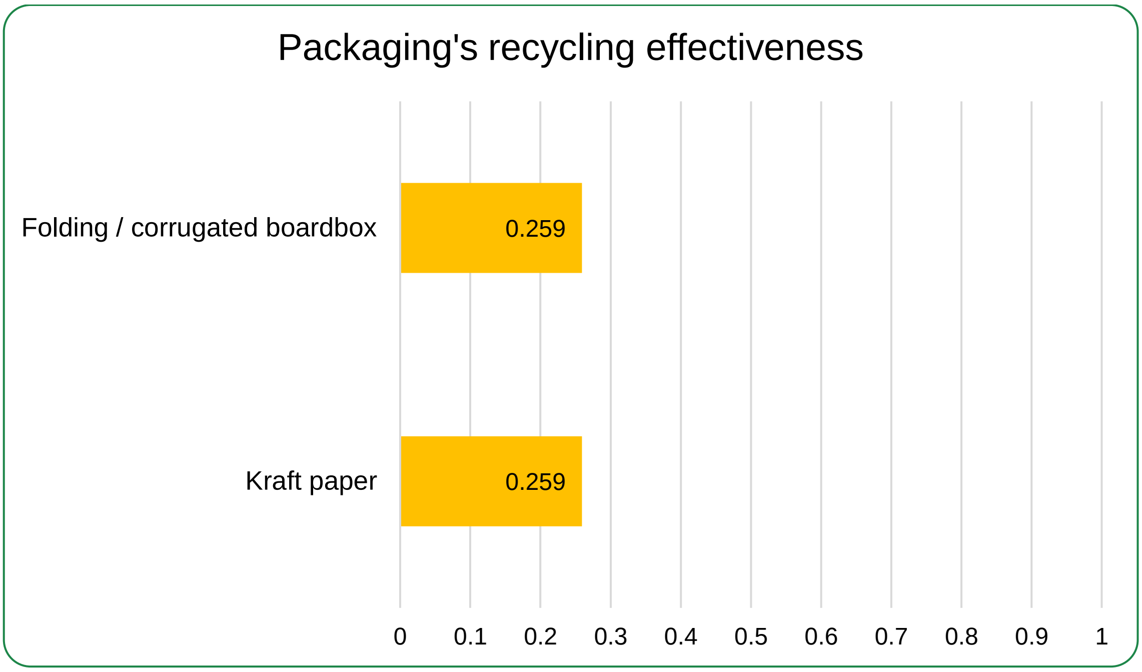

Figure 10: *Packaging's recycling effectiveness results.*

For the calculation of recycling effectiveness, data for only two materials was made available; more specifically, those coming from BIORADAR's work package 1. Data related to Preserve project was not available with the granularity level required, thus its recycling effectiveness could not be calculated.

On the other hand, both cardboard and paper share the same recycling process (wood pulp recycling), thus their recycling effectiveness results are the same, as can be seen in **Figure 10**.

This value can be compared to those generated by Roithner (2021), who applied the indicator to PET recycling. Despite being different materials and different recycling processes, the results were coherent with the recovery rate of the target material, as shown in **Table 11**. Results obtained by Roithner (2021) highlight that two systems having the same recovery rate could have two different recycling effectiveness results (i.e., 0.21 and 0.23), since it depends not only on how much of the target material is recovered but also on the level of purity achieved in its recovery.

Table 11: *Recovery rate and recycling effectiveness of wood pulp and PET.*

	Target material recovery rate	Recycling effectiveness result	Source
Wood pulp recycling	0.96	0.259	For the recovery rate: Tran & Vakkilainnen (n.d.) and European Commission (1999)
PET	0.70	0.22±0.01	Roithner (2021)

Ultimately, these results represent the gap between the achieved concentration of the target material and the maximum (theoretical) potential of the system to concentrate it.

Also, for the calculation of the wood pulp recycling effectiveness the following data was coupled with that received from WP1:

- From Datambient asesores et al. (2012) the maximum allowable content of improper materials in recycled wood pulp.
- From Revista Técnica de Medio Ambiente (RETEMA, 2017) the amount of improper materials coming from selective paper and cardboard collection.
- From Ecoembes (2012), the maximum allowable content of improper materials in selectively collected paper from commercial and industrial settings.

On the other hand, virgin material consumption index results are displayed in **Figure 11**.

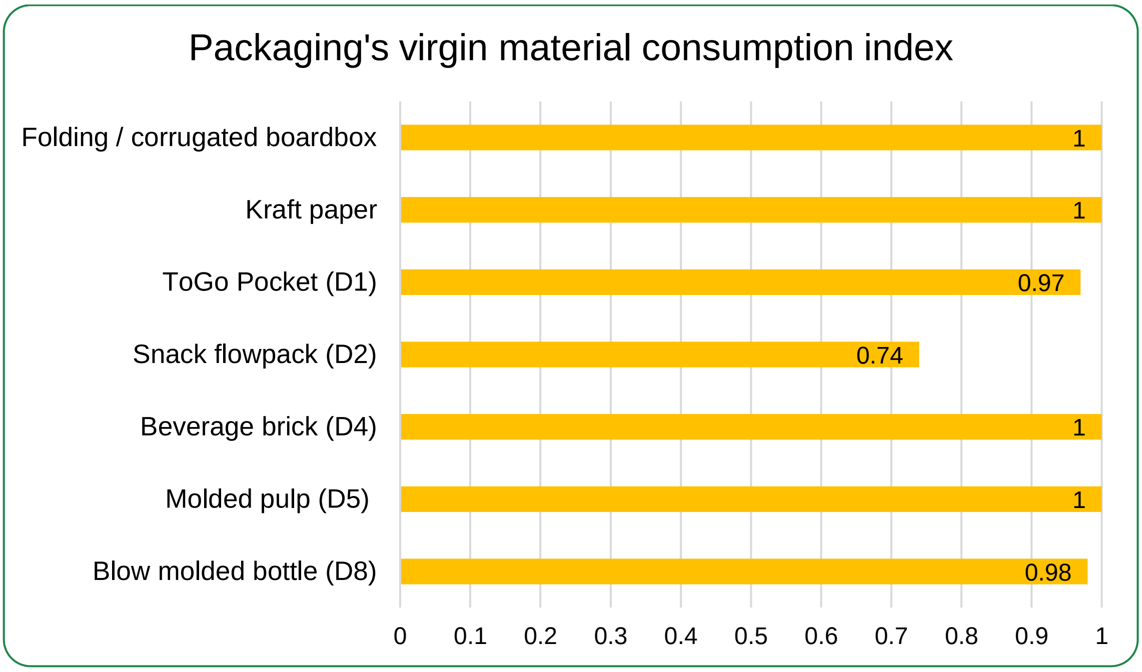

***Figure 11**: Packaging's virgin material consumption index.*

As shown in **Figure 11**, all the products obtained high scores (> 0.74). This is consistent with the fact of all being bio-based products.

The products scoring lower than 1.00 are precisely those multi-material ones requiring virgin materials in their composition. For instance, the ToGo pocket incorporates 2.10% of protective lacquer and 1.34% of PVOH coating. Similarly, the snack flowpack incorporates 25.97% of metalized PET (i.e., PET met). The same happens in the blow molded bottle, which contains 2.50% of Yparex (a registered brand of ethylene-vinyl alcohol copolymer, EVOH).

For these products, the virgin material consumption index is quite straightforward, highlighting the presence of even small quantities of virgin materials, which reduce the circularity of the products.

3.4 TEXTILE INDICATORS

Regarding textiles, the BIORADAR circularity measurement framework is comprised by the resource pressure indicator, whose results are presented in **Figure 12**, and the fibre treatment circularity index, with its results displayed in **Figure 13**.

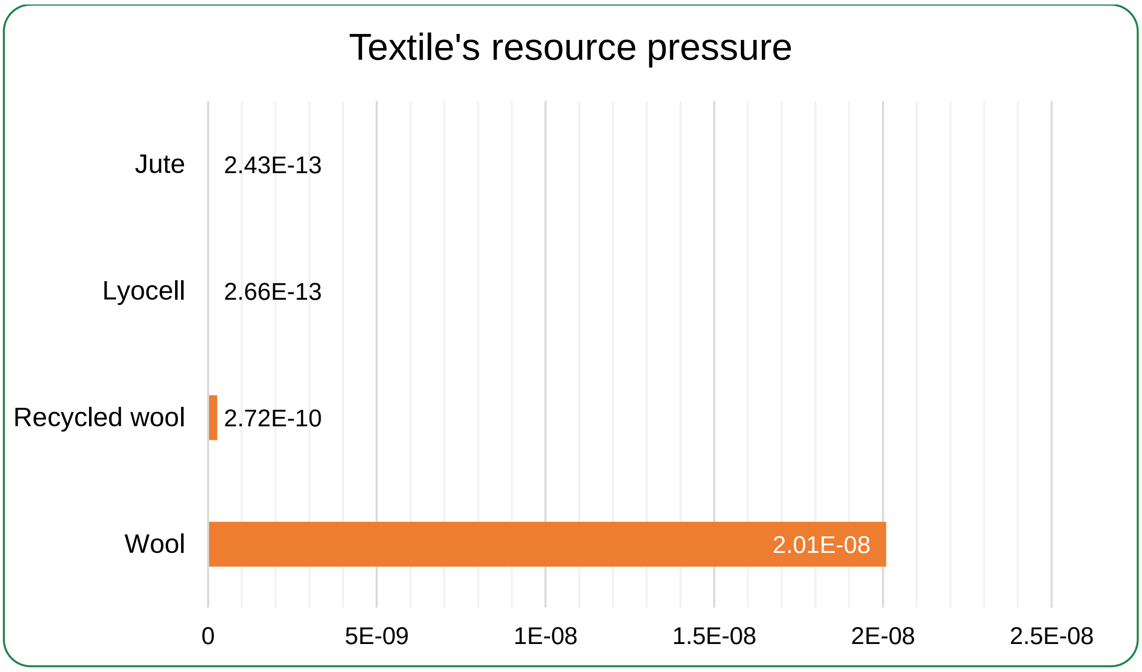

Figure 12*: Textile's resource pressure results*

The chart for **resource pressure** changes the style used for all the other figures in the report. Here, the bigger the bar, the higher the pressure the product exerts on the environment. This means that the most circular product would be that with the lower resource pressure.

For the assessed products, wool is the one with the highest resource pressure, followed by recycled wool (two magnitude orders smaller than the virgin option). Jute and lyocell are the ones with the smallest resource pressure, being five magnitude orders smaller than virgin wool.

Such small results are aligned with those published by Desing et al. (2021), specifically for Cu/Al alloy options, all of them being in the order of 10^{-12}. Other authors have published resource pressure results as a percentage of a baseline (Lama et al., 2022). That may make simpler to understand and work with the results, but for the case of this report, it was not possible to apply given the fact that no baseline was set for any of the products.

Of particular interest within the calculation of this indicator is the concept of **Environmental Resource Potential** (ERP). For the calculation of these values, the only unit impacts available were global warming potential (GWP) and ozone depleting substances (ODS). The results, and the corresponding limiting boundary for each product are detailed in **Table 12**.

Table 12*: Environmental Resource Potential and limiting boundaries for the assessed textile products.*

Product	ERP	Limiting boundary
Jute	$4.33x10^{11}$	Global warming potential
Lyocell	$5.63x10^{11}$	Global warming potential
Recycled wool	$5.63x10^{8}$	Ozone depleting substances
Wool	$7.70x10^{6}$	Ozone depleting substances

As can be seen in **Equation 16**, ERP is placed in the denominator, dividing the mass of product. So, the bigger the ERP, the lower the resulting resource pressure.

Finally, the **fibre treatment circularity index** results are presented in **Figure 13** and discussed below.

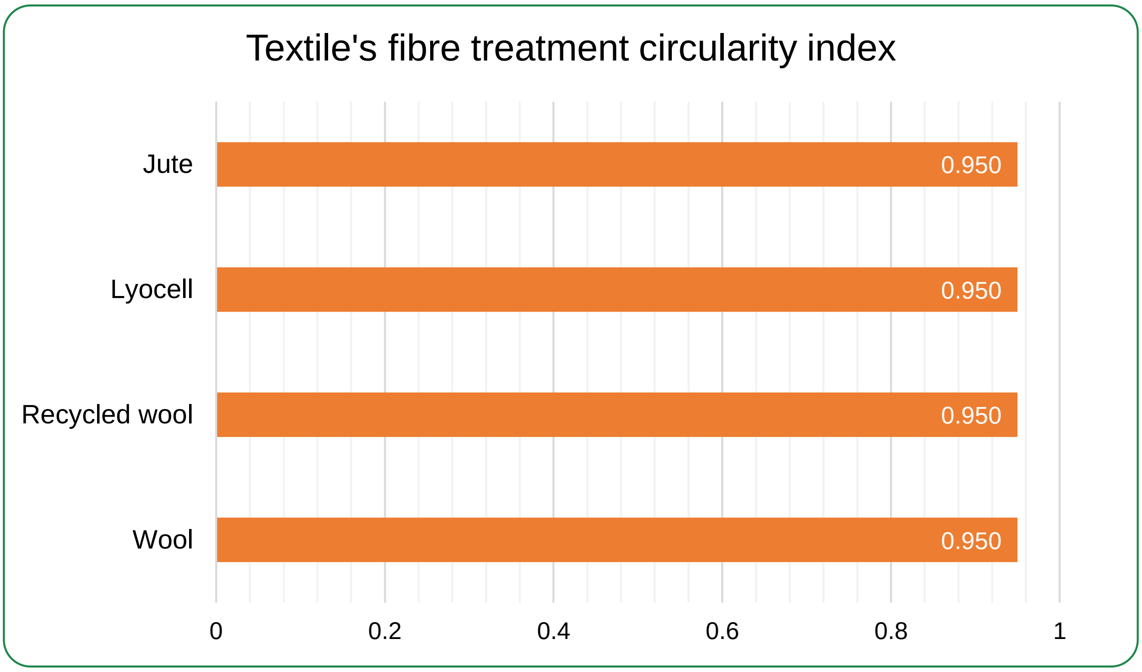

Figure 13*: Textile's fibre treatment circularity index results.*

Fibre treatment circularity indicator was calculated with the data available from BIORADAR's Work Package 1. With that information, the calculation resulted in the same index for all the products. The data available was comprised of the fibre's finishing stage, which consumes soap, silicone and chemicals, in equal amounts for all the cases. Compared to the mass of treated fibre, all these consumptions represent a small amount of resources, thus attaining high treatment circularity levels.

4. CONCLUSIONS AND NEXT STEPS

Circular economy is opening its way from the academic and policymaking environment into management. Logically, what cannot be measured, cannot be managed, and the key tool for managing the sustainable transition are indicators.

This document has built upon previous reports developed by BIORADAR project, mapping, assessing and selecting available circular economy indicators for bio-based products. Going further, those **indicators were assessed by identifying their gaps, and these were bridged with proposals of complementary metrics**. As a result, **BIORADAR product circularity measurement framework was built** and is hereby presented and validated.

Validation was conducted by calculating the indicators for a sample of targeted bio-based products, and by direct contact with producing companies. The results offer a **first database of circular economy indicators**, which can serve as a reference for industry, policymakers and academia, and that will be incorporated into BIORADAR digital monitoring tool. Contact with producing companies demonstrated that **industry agents are interested in measuring their circular economy**, **have relevant measurements** to some extent, and regard the proposed framework as a **useful and promising tool to assess the circularity levels** of their products **and to steer their sustainable transition**.

Regarding **circular index**, its main identified advantage is that it **aggregates different circular characteristics into a single numeric value**. Having a single value has both its upsides and downsides. On the one hand, **it allows having an idea of the circularity of a product at first sight**; **on the other hand, a single value does not allow to further identify specific advantages or improvement possibilities**.

When calculating the circular index, it became clear that **the material part of the indicator has a lot more impact in the final value than the energy part**. If the energy factor is taken out of the calculation (i.e., setting all energy consumptions to zero), the variation of the result ranges between 0.05 and 1.19%, which is rather negligible. This allows to affirm that, for even further simplification, **circular index calculation could be conducted without considering energy consumption and still obtain a fair product circularity assessment**.

Notwithstanding, **the indicator is not be able to differentiate between different types of renewable resources consumption**. For instance, for textile materials, the water consumption made the circular index to increase. It may be counterintuitive to affirm that a product that requires greater water amounts is more circular, and rightly so. **Since the circular index considers the ratio between non-renewable and renewable, if the difference between them is too big, the indicator accounts for increased circularity**. Therefore, when this case happens, the indicator should not be reported alone and as the ultimate circularity assessment, but complementing it with its corresponding analysis and critical evaluation.

Another relevant aspect of the circular index is the fact that it requires **system boundaries** to be set. For other indicators this may not be necessary as they may be sufficiently clear not to allow user interpretations. But circular index actually calculates the circularity of the manufacturing process, so if a material output is treated as a waste, a co-product or if its valorised to generate heat or power, it would have different effects on the final result of the indicator. This means that **the very same product may have different circularity indices, depending on how the manufacturing process had been set up**.

This is not only true for the index but also for circularity as a concept. The production of a bio-based product may be more or less circular depending on many other variables apart from it harnessing waste streams and turning them into value-added products. Some aspects that may seem out of scope, like whether a material output is treated as a waste, a material to be reused or recycled by someone else, are relevant for circularity assessment. This may depend on the installed capacity of the region or the sector to, for instance, recycle a specific material stream: if a factory is based on a region where such material can be reused or recycled its circularity level will be higher than that of an identical factory that has no other option than sending that material to landfill.

This emphasises the fact that **achieving circularity is not only a challenge for single companies, but for the economy as a whole, and that the circularity level of a single economic actor is dependent on the circularity of other actors surrounding and engaging with them**.

As for **biodegradable/compostable content**, it was identified as a valuable complement to the circular index. It **allowed to identify nuances among products**. Even though for bio-based products both indicators tend to be high, having biodegradable/compostable content alongside circular index helped to detect when non-biodegradable/compostable materials had a relatively high weight in the final product mass. This gains particular relevance when having the lens of **circular bioeconomy**, where the **avoidance of non-renewable material consumption** is a common goal.

Regarding fertilisers, the **circularity indicator of nutrient** has proven to be an effective **indicator of nutrient recovery efficiency**, as a way to assess the manufacturing process. In reality, the indicator is **not measuring the circularity of a product alone but rather of a specific production process**. Spent mushroom substrate, for example, resulted in a wide standard error because of the variety of raw materials used for its production, and the different yields attained for recovering nutrients.

When assessing the **nutrient slow release index**, the main obstacle found was the scarcity of required data to calculate it. Even when one of the main competitive claims of bio-based fertilisers is its slow release of nutrients, scientific data is not that abundant at the moment; at least for the products assessed in this report.

In terms of packaging, the **recycling effectiveness** indicator proved to be an indicator composed of simple **data points, available in overall and component-wise mass balances of recycling systems**. Logically, it is **only applicable to recycling processes**, as it measures its capacity to concentrate target substances. The numeric result by itself may be confusing, but **when compared to a baseline may turn out useful for decision making**.

Concerning the **virgin material consumption index**, its data availability was confirmed, and allowed to highlight the *other side of the coin* regarding circularity: the use of linear materials.

From the textile point of view, **resource pressure indicator** turned out to be comprehensive by including planet boundaries and product lifetime alongside more common material circularity aspects. However, the numeric value of the indicator may be hard to interpret and is better understood when comparing it to a baseline, which was not possible under the scope of this study.

Finally, the **fibre treatment circularity index** also gives a sense of non-renewable material consumption during the fibre's final treatment. Logically, it depends on the treatment data, and may have subtle nuances depending on the specific fibre and treatment. It sheds light on a relevant stage of the fibre production process. When the only non-renewable materials involved in the fibre production process are those used in the fibre treatment, this indicator may reflect the same concepts embedded in the biodegradable content indicator, but from a different point of view.

Having analysed the proposed framework, it is evident that **circularity is highly dependent on the production process**; the decisions made —or options available— regarding material sourcing and transformation, waste disposal, and energy consumption affects the circularity levels, even when applied to the same final product.

Also, given the nature of the assessed products, **circular practices linked to the use phase** (like sharing, repairing, product-as-a-service, refurbishing, remanufacturing, etc) were not accounted for. But when applicable, accounting for these practices can also **impact the circularity indicator results**. This means that the very same product, manufactured in the same way, may attain different levels of circularity, depending on the use given to it by the consumers.

Data collected and results obtained during the development of this report are to be **incorporated to the BIORADAR digital tool** to be launched soon. To enhance the database, additional emphasis into incorporating direct industry values will be put, with the aim of raising the quality of the subjacent data. This means that the BIORADAR digital tool's circularity module will not be limited to the products and data reported in this document, but it will rather be fed with more products and cases that because of time constrains could not be included in this report.

In regards to **research areas that still need further development**, the one with the more critical situation is the **nutrient release speed of fertilisers.** It is particularly relevant because it is useful for assessing the circular economy's principle of slowing resource loops, and it directly addresses one of the main environmental problems currently: the leakage of nutrients from agriculture practices, causing extended eutrophication problems in ecosystems. Data required needs to be fertiliser-specific, and coupling the bio-based product with a non-renewable counterpart.

Nutrient release speed is ultimately related to the use phase of the product. Other **use-phase-related circularity aspects** were not included in this study (for instance, for textiles and packaging) because of lack of quantitative data and the approach taken in the study (assessing materials and not finished products). When assessing finished products, the suitability of a product to be **reused, shared, repaired, leased, etc**. has an impact on its circularity level.

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