Circularity in the bio-based packaging industry
03/2021

D8.6: Case study “Circularity in the bio-based packaging industry”

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Monitoring the Bioeconomy

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N°773297.

Technical References

Project Acronym	BIOMONITOR
Project Title	Monitoring the Bioeconomy
Project Coordinator	Justus Wesseler Wageningen University justus.wesseler@wur.nl
Project Duration	June 2018 – May 2022 (48 months)

Deliverable No.	D8.6 – Case Study "Circularity in the bio-based packaging industry"
Dissemination level [1]	Public
Work Package	WP 8 – Case Studies
Task	T 8.2.5 – Circularity in the bio-based packaging industry
Lead beneficiary	17 – NOVA
Contributing beneficiary(ies)	8 – CBS, 14 – DTT
Due date of deliverable	31 March 2021
Actual submission date	31 March 2021

1 PU = Public
PP = Restricted to other programme participants (including the Commission Services)
RE = Restricted to a group specified by the consortium (including the Commission Services)
CO = Confidential, only for members of the consortium (including the Commission Services)

Document history			
V	Date	Beneficiary	Author
0.1	02.03.2021	nova	Florian Dietrich, Christopher vom Berg
1.0	31.03.2021	nova	Florian Dietrich, Christopher vom Berg

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0 Summary

This case study investigates the potential of monitoring the circularity of bio-based packaging via the calculation of so-called circularity indicators. It is part of the Biomonitor project and therefore also looks at the implications the results have on this project. As Biomonitor seeks to monitor the EU Bioeconomy, the data acquisition and the indicators could be an example of how to approach this task. One key goal of this study is to show to which extent the circularity of the biobased packaging industry can be described by using two selected indicators, the Material Circularity Indicator (MCI) and the Biomass Utilization Factor (BUF), which is a new indicator still under development by nova-Institute and which is further investigated in WP3.

In order to be able to calculate the circularity of the indicators, it is necessary to obtain the data needed for the calculations. Here, a two-pronged approach is undertaken, where it was attempted to obtain required data 1) via personal interviews with relevant value chain actors and 2) via official statistics and literature resources.

The data requires information on packaging compositions, sourcing of their feedstock, lifetimes, and their end-of-life treatments. In order to get an overview of available data, the biobased packaging types and their circularity are described in two chapters. This helps to gather relevant data and replace missing data with derivations and comprehensible assumptions. It also gives an overview of the current status of this industry and its basic drivers and barriers. As a key take-away, this study shows that there is very little data available publicly, and most companies are not willing to collect and share data regarding the material composition or circularity of their products due to confidentiality or lack of relevance for their daily business. This is likely a larger issue for the implementation of a monitoring system, and new approaches regarding the accessibility of data might be necessary.

Three consumer and industrial packaging examples based on available literature data and statistics are used to test both indicators and explore the availability of data. The study shows that both indicators are helpful for monitoring the circularity of the bio-based packaging industry. The indicators complement each other by accounting for the biobased aspect on the one hand and the circularity of other materials, product lifetimes and recyclate feedstocks on the other hand. Although the data collection is complicated and needs to be supported by additional publicly available data in the future, the resulting values can be seen as good indicators for the circularity of the specific products. If data can be delivered in a more detailed (e.g. product groups for a specific country) and on a regular basis, the chosen indicators are promising candidates for the biomonitor project.

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1 Introduction

This chapter defines the research questions and the scope of the study. It is asked for the general objective of the study and which elements are included while other elements are left out. This chapter therefore sets the frame and aim for the study.

1.1 Research questions

This study analyses the current status of the bio-based packaging industry regarding circularity and researches possibilities to monitor the developments in this sector. In this study, the circularity of the bio-based packaging sector is analysed by the use of two indicators which calculate important features of the circular supply chain, e.g. recycling rate, lifetime, biomass utilization etc.

The first question to be asked is **what materials can be seen as bio-based packaging materials**? This question is dealt with in chapter two.

In the next step, the specific value chains of the bio-based materials used for packaging are considered. This step is needed to provide information on which data needs to be collected for each specific value chain/ each material in order to calculate the circularity. This may differ depending on the considered material which is why it needs to be evaluated individually. The resulting question would be: **How does the value chain including the end-of-life of each bio-based packaging material look like?** This question is being answered in chapter three.

As soon as the life-cycle of each material is evaluated, necessary data needs to be collected in order to calculate the circularity indicators. In the first step, the indicators, the Material Circularity Indicator (MCI) from the Ellen McArthur Foundation and the Biomass Utilization Factor (BUF) from the Nova Institute, are described concerning their informative value on the circularity and their data requirements. This brings up the following questions: **What are the indicators measuring and how does this relate to the definition of circularity? Which data is required for the calculation of these indicators and what data is publicly available? Missing data needs to be replaced by derivations, how can this data be replaced?** These questions shall be regarded in chapter four.

Chapter five deals with three examples from the bio-based packaging industry and asks how the required data can be obtained for these specific cases and what assumptions need to be made in order to calculate both indicators.

Chapter six and seven ask and answer the concluding questions: **To what degree do these indicators monitor the circularity in a way that is helpful for the Biomonitor project? And, can this approach be generalised for a regular calculation in the Biomonitor project? If this is not the case, what needs to be done to make this possible?**

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1.2 Scope of the study

In order to answer the mentioned research questions, a frame for this study needs to be set which defines what aspects of the bio-based life-cycle are considered and which are left out.
This study researches the current status of the EU-27 bio-based packaging industry. The industry can be best described by looking at the supply-chains of different packaging materials. Common packaging materials are plastics, paper & board, wood and composites of different materials.

As this study is titled "Circularity in the bio-based packaging industry", the materials considered are bio-based packaging materials. Any such material is at least partly bio-based and, therefore, not exclusively fossil-based. The specific material types and their packaging applications are described in **chapter two**. Both B2C (consumer) and B2B (industrial) packaging is considered in the study. The term circularity involves the investigation of the full life-cycle of a packaging product, including end-of-life treatment. It includes the end-of-life options of reuse, recycling and (energy) recovery of the materials, i.e. everything that contributes to a more circular in contrast to a more linear/ single use.

The specific "circularity systems" in place, which comprise the infrastructure, technologies and waste management but also the willingness of local companies and customers to use circular products and materials, are described for different packaging materials in **chapter three**. This chapter does not consider each end-of-life treatment for each material in every member state individually but focuses on the most common practice for each material in the EU. While there are some EU policies which obligate the member states to introduce and sustain systems for waste reduction, the specific design of such systems is in the responsibility of the individual member state. This means that specific end-of-life treatments can differ from state to state. These differences occur especially regarding the collection type for different materials (consumer dropoff vs. collection at home) but have negligible consequences on the calculation of the indicators in the next chapter, which is why they are not considered in detail in this case study.

Chapter four describes the methodology of how to research questions were investigated. Here, a two-pronged approach was attempted to acquire the necessary data: 1) was investigating available literature and statistics like EUROSTAT to collect required information, 2) was direct interviews with actors of the value chain to see whether these actors have the necessary information available and are willing to share. Additionally, we describe two indicators that qualify as a potential tool for monitoring the circularity of bio-based packaging. These indicators are the BUF (Biomass Utilization Factor) and the MCI (Material Circularity Indicator). The BUF considers the use and reuse of biomass in products, while the MCI considers a number of different measures like the collection rate, the amount of virgin raw material and the lifetime of the product. This chapter will show the limits of available data and information which is necessary to calculate the indicators.

In **chapter five** the indicators are calculated, and the results are presented and discussed. This chapter focuses on compiling the results of the indicator calculation. It also explains and compares the results of the indicator calculation and what these results implicate. The approach and scope of this chapter is limited to the examples and the used indicators.

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Chapter six concludes this case study by summarizing the key findings on the different value-chains for each packaging material, what this means for the circularity as a whole and for the data acquisition and calculation of the two indicators. This chapter points out the challenges the packaging sector is confronted with when moving towards a more circular bioeconomy and how the monitoring of this development can be designed in a useful way.

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2 Bio-based packaging

2.1 Overview

„Bio-based products are products that are wholly or partly derived from biomass: Material of biological origin, such as from trees, plants or animals."[1] Bio-based means „composed or derived in whole or in part of biological products issued from the biomass (including plant, animal, and marine or forestry materials)."[2]

In this study, only bio-based packaging is considered. However, the materials in question are not always fully bio-based but can be partially petroleum-based or of other origin (e.g. minerals). This characteristic is significant as the BUF indicator measures the share of biomass in the product and subsequent products. Bio-based packaging itself contributes to a sustainable economy by reducing the use of fossil carbon. This is in line with the renewable carbon concept, developed by the Nova Institute which states that in order to prevent growing CO_2 emissions humanity needs to cut down the use of fossil carbon and instead use and reuse renewable carbon. This renewable carbon can be sourced from biomass, CO_2 or by recycling carbon-based materials. Bio-based should not get mixed up with the term compostable, bio-based plastics for example are often not compostable in the common sense and need end-of-life treatment like recycling. Many materials are not suitable for direct use as packaging material due to providing an insufficient barrier or insufficient mechanical properties.

2.2 Bio-based plastic packaging

Plastics are made of polymers which are chains of repeating monomers, containing carbon and hydrogen (major building blocks) and sometimes oxygen, nitrogen, chlorine and phosphine. In order to be considered as bio-based plastic these building blocks have to be at least partly of bio-based origin.

Independent of the source the plastic can be divided into two subgroups: Thermoplastics and Thermosets. The former describes plastics which undergo chemical changes in their composition when heated. This property allows these polymers to be moulded repeatedly. Some examples are polyethylene terephthalate (PET), polyethylene (PE), polyvinyl chloride (PVC), polypropylene (PP) and polystyrene (PS). This group of polymers represents 85% of the produced amount in the EU.

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[1] European standards supporting the market for bio-based products, CEN/TC 411 2014 https://www.cen.eu/news/brochures/brochures/CEN_Bio-based-products_2014.pdf (accessed: 03/18/21)

[2] Vert, M., Doi, Y., Hellwich, K., Hess, M., Hodge, P., Kubisa, P., Rinaudo, M. and Schué, F. (2012) Terminology for biorelated polymers and applications (IUPAC Recommendations 2012). Pure and Applied Chemistry, Vol. 84 (Issue 2), pp. 377-410. https://doi.org/10.1351/PAC-REC-10-12-04

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Each year hundreds of different types of thermoplastics are introduced to the plastics market which makes the sorting and recycling of these materials at end-of-life more complicated.
Thermosets are plastics which are strengthened when heated. Examples for this group are polyurethane (PU), epoxy resins and phenolics. They account for 15% of the EU plastic demand.

The properties of (bio-based) plastics can be further engineered by using fillers, plasticisers and additives. Fillers are used to improve properties and reduce manufacturing costs. Plasticisers modify the flowing properties and additives add specific functions like flame resistance. Moreover, to improve properties the chain-length, chain composition and chain structure of the polymer can be altered. This possibility to customize the polymers to specific needs improves marketability but also has the downside that it hampers end-of-life treatment.[3]

The most common bio-based plastics, considering the production amount in t/a for 2019 are Epoxy resins (1,000,000 t/a), cellulose acetate (770,000 t/a), starch-containing polymer compounds (360,000 t/a), polyurethanes (310,000 t/a), polylactic acid (270,000 t/a), polyamides (220,000 t/a), polyethylene (160,000 t/a) and polytrimethylene terephthalate (160,000 t/a). From these materials only starch-containing polymer compounds, polylactic acid, polyethylene and polytrimethylene terephthalate are used for packaging. Their bio-based content can range from 5% (PTT) to 95% (PE). Other polymers like polyhydroxyalkanoate (PHA) and polyethylene furanoate (PEF) are on the rise but are too expensive at the moment. Other bio-based materials are currently used in the form of composites (cellulose & starch) or can be used as coatings (proteins, lipids & waxes).[4]

Bio-based plastics are often (not always!) more sustainable regarding their global warming potential than fossil-based feedstocks and in some cases have improved functionalities like enhanced breathing capability, antistatic properties or the absence of toxic substances. Additionally, bio-based materials can transport a positive image to customers, for example in regards to naturality.

2.3 Paper & board packaging

The primary raw materials for paper & board are cellulose fibres which can either be obtained from trees or by recycling paper. The European paper industry uses 86% renewable raw materials (46% fibres of recycled paper & 40% wood pulp), the remaining 14% are non-fibre substances, e.g. calcium carbonate. 90% of the wood is obtained from forests within the EU, of which 60% are treated sustainably. In order to obtain paper & board as a product, the fibres are mixed with water and placed on a sieve. The water is drained and a sheet of paper is obtained. Several sheets are pressed, heated and coated before being cut to the desired size. This material is used for packaging of small- to medium-sized consumer freight and small industrial freight transport as well as food (sometimes in form of laminated/ polymer coated board). The most common board materials are white lined

[3] Blueprint for plastics packaging waste: Quality sorting & recycling, Final report, Deloitte Sustainability

[4] Skoczinski, P., Carus, M., de Guzman, D., Käb, H., Chinthapalli, R., Ravenstijn, J., Baltus, W., Raschka, A., Bio-based Building Blocks and Polymers – Global Capacities, Production and Trends 2020 – 2025

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chipboard (mostly from recycled fibres), folding box board, bleached and unbleached solid board (mostly from fresh natural fibres).[5]

2.4 Wood packaging

Wooden packaging includes pallets, pallet collars, box pallets, boxes, crates, cable drums, lightweight packaging for fruit and vegetables, barrels, tailor- made constructions, and dunnage for supporting goods under transportation. In many cases quality standards ensure that performance is sufficient to protect the goods transported. Pallets are by far the most common type of wooden packaging. Although there are standardized versions, pallets are produced in many sizes and configurations to accommodate different handling equipment generally forklifts, cargoes, space constraints and required longevity. Pallet collars are used widely, such as for the transport and storage of small parts in the assembly industry. Foldable pallet collars with lids and bottoms can create demountable boxes for simple, cheap return transportation and storage. Lightweight packaging includes crates, cases, boxes and small drums; it is used mainly for processed or fresh food, beverages, and other consumer goods demanding quality and protection. Cable drums are used by cable manufacturers in the electrical, electronics and telecommunications sectors.

Most wooden packaging in Europe is made of softwood produced in sustainably managed forests and currently it is estimated that about 4 billion pallets are in circulation in Europe. The average lifespan of a pallet is 5-7 years. The pallet and wooden packaging industry in Europe consumed more than 20 million m^3 of sawnwood in 2015, which was more than 20% of total sawnwood production. When the economy improves, so does the pallet and wooden packaging industry. Pallets are manufactured to standards or custom-made. There is a high degree of standardization in Europe based on the modular size of 600 x 400 mm. The major pallet sizes in Europe are 800 x 1,200 mm (this size is used for the example calculation) and 1,000 x 1,200 mm, but half-pallets (600 x 800 mm) and quarter-pallets (400 x 600 mm) are also produced. The UK and Benelux export markets, where 1,000 x 1,200 mm pallets were previously the standard, are switching to the EUR pallet of 800 x 1,200 mm.[6]

The key advantages of wood are good protection against damage, good strength & impact resistance, good rigidity and good stackability. Wooden crates are increasingly being replaced by cheaper plastic containers. For products such as wine and spirits, wooden barrels offer an additional function of assisting the maturation process by imparting flavours that enhance the quality of the product. Wooden packaging is also used to give products a more luxury or expensive image.[7]

In the end of 2017 the Religno consortium, an Italian consortium whose members obligate themselves to reuse and recycle their wooden packaging products, sold about 3 million tons of wooden packaging. Of these products 72% were new and regenerated pallets, 14% industrial

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[5] Vergleich von Karton und Kunststoff Nachhaltigkeit in der Verpackung, Pro Carton, Mai 2018

[6] Trends and perspectives for pallets and wooden packaging, United Nations Economic and Social Council, https://unece.org/fileadmin/DAM/timber/meetings/20161018/E/ECE_TIM_2016_6_FINAL_wooden_packaging.pdf (accessed 01/20/2021)

[7] Molenveld, Karin & Van den Oever, Martien & Bos, Harriëtte. (2015). Biobased Packaging Catalogue.

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packaging, 1% reel, 9% wooden crates for fruit and vegetables, and 4% consumer packaging materials. This shows that there is a big market for recycled or reused wooden materials which is often not served due to a lack of infrastructure.[8]

2.5 Composite packaging

Basically, any material that consists of fibres and a binder (e.g. resin, polymer) can be called a composite. "Biocomposite" is a collective term to refer to fibre-reinforced materials with partly natural origin. Fibre content ranges from 15% up to 75% depending on application and production method. Most producers still use fossil-based polymers for the production of biocomposites. The most important are:

- PE (decking & construction, consumer goods, extrusion)
- PP (automotive, construction, consumer goods, injection moulding, 3D printing)
- PVC (decking & construction, extrusion)
- To a smaller amount: ABS, Epoxy, PA, PMMA, PS, PU, TPE, TPS, TPU

There are a lot of bio-based polymers on the market to produce partly or fully bio-based composites, to use renewable carbon instead of fossil carbon. Some are biodegradable. Examples: Bio-PE, PLA, Bio-PBS, Bio-TPE, PHA, PHB, and Bio-PP. Recently the use of recycled (side streams or post consumers) polymers has increased.

(Bio-)Composites are mostly associated with food packaging like the packaging of dairy products & snacks or squeezable packaging. These composites are used to maintain the freshness of the food while at the same time making it transportable and consumer-friendly. The most common composite packaging is probably the milk carton, which is made from double-sided PE-laminated paperboard. 90% of the paperboard used for milk cartons produced in the EU is sourced from forests in Sweden and Finland and produced by only three major companies: Tetra Pak, Elopak and SIG Combibloc. These companies are currently working on making their milk packaging 100% bio-based. This can be achieved by replacing the fossil-based PE for the cap and lamination with bio-based residues like sugarcane from Brazil or tall oil from Nordic forests. Examples include the Tetra Rex® and the Pure-Pak bio-based milk cartons.[9]

Even though most people associate composites with food packaging, the biggest producer of composites in the EU (50,000 - 100,000 t/a), Amorim, is based in Portugal and produces composites of cork and polymers to be used as flooring materials The second-largest producer Beologic (10,000 – 20,000 t/a) uses plant-based materials in combination with fossil-based polymers to produce polymer-type granulates which can be used as drop-in solution for PE, PVC, PP, PS and ABS. Other

[8] Best practices in the wood recycling sector, Case study by Marco Gasperoni, Lead Director of the Rilegno consortium

[9] Composite packaging, Design Smart Material Guide No. 8, Australian Packaging Covenant http://www.helenlewisresearch.com.au/wp-content/uploads/2014/03/Composite-DSMG-082013.pdf (accessed: 01/25/21)

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smaller European producers with production ranges of up to 10,000 t/a also use hemp, flax, sun flower or other natural and cellulose fibres, bamboo, corn cob, rice husks or straw as raw materials. These materials present a more sustainable alternative to fossil-based packaging but are limited by feedstock availability as they compete for farm land with food and feed for animals[10].

2.6 Glues

Glues are also called adhesives and are used in the packaging industry to combine different materials or to stick together different parts of the packaging material e.g. packages for mail delivery. Most adhesives can be attributed to one of the following categories[11]:

- water-based systems: Solutions of PVA, gluten, casein, dextrin, starch or emulsion adhesives. Also, latexes which are a stable dispersion of a polymeric material in aqueous medium.

- solvent-based systems: Combination of adhesive material with a suitable solvent. These high-performance products are created using a polymer with a stable molecular structure, which complements the chosen solvent. Growing environmental concerns over VOC emissions is anticipated to hinder the growth of solvent-based adhesives over the next decade.

- hot melts: Bonds which are responsible for the sticking characteristic are formed by cooling down. This makes their application perfect for cases in which strong and efficient adhesives are needed which form immediate bonding. These types of glues are widely utilized in packaging applications.

From a sustainability point of view the adhesives themselves are negligible due to their small amounts in the overall packaging, which can be even further reduced by using more efficient glue patterns. Nevertheless, about 20 – 30 % of the glues contain bio-based shares of 15 – 50 % e.g. natural latex/ rubber, methanol/ ethanol/ ethyl acetate from sugar cane or waste streams, terpenes, glycerol and epoxies from castor and soy bean oil.

What is more relevant is the ability to detach the adhesives from the packaging in order to improve recyclability. This is especially important for adhesives used in composites which consist of different layers which need to be separated to be recycled. This is why easily peelable sealants are increasingly familiar in tray/ lid and cartonboard/ film applications. Solutions such as Dow's APPEEL and Bostik's dual resin system are examples of adhesives that offer reliable separation.[12]

[10] Carus M. & Partanen A. 2019, Biocomposites: Reducing the use of plastics without changing production technology?, https://renewable-carbon.eu/publications/product/biocomposites-reducing-the-use-of-plastics-without-changing-production-technology-%e2%88%92-full-version/ (accessed 02/03/21)

[11] Industry Insights Packaging Adhesives, Grand View Research, https://www.grandviewresearch.com/industry-analysis/packaging-adhesives-market (accessed: 02/03/21)

[12] Adhesives Snapshot, Tim Sykes, Packaging Europe, https://packagingeurope.com/adhesives-snapshot/ (accessed: 02/18/21)

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2.7 Inks

Inks are used in packaging to print information about the product or the supplier or for shipping on the material. While traditional printing of books newspapers and graphics is decreasing, the amount of inking in packaging is increasing. Inks consist of colorants (pigments or dyes) and a vehicle (binder). The vehicle is used to bring the colorants on the material. In most cases these vehicles are water or a solvent. Different applications in packaging need different compositions and types of these two ingredients. The ingredients depend upon the material the ink is printed on, the time for drying and the desired costs and quality of the print.

Concerning sustainability, one can differentiate between ecological and non-eco inks. Most non-eco inks have toxic elements that cause further harm to the environment, and human health too. The solvents often contain minerals, whilst the pigments often contain heavy metals like lead, mercury or cadmium, which can migrate to the wider ecosystem when left to biodegrade. The elimination of these heavy metals is now compulsory in many markets – though not yet in packaging in China. Volatile Organic Compounds (VOCs) are a byproduct of traditional inks and a potential hazard for humans and the environment.[13]

Biodegradable inks are based on naturally biodegradable vegetables oils such as soya or rapeseed instead of minerals. There's a misconception that environmental alternatives such as biodegradable inks are more expensive. In fact, many biodegradable alternatives are more cost effective as they flow and spread more efficiently than conventional ink, ultimately reducing the amount of ink needed in the printing process. Biodegradable inks often also produce more satisfying, vivid colours and have a better smell compared to traditional mineral-based inks.[14]

Water-based inks are also more environmentally friendly as they eliminate solvents which are mostly petroleum-based and increase VOC-emission. However, these inks need more time to dry. Other, more environmentally-friendly alternatives are UV (ultraviolet) and EB (electric beam) curable inks which do not need a solvent and inks based on pigments from algae.[15]

Inks do not influence the quality of packaging recycling in a direct way but impact the color of the recyclate. Projects conducted on recycling flexible packaging have shown that the final recycled polymer is a grey/green colour. This can limit the end market applications the recycled plastic can be used in. Trials in the Reflex project demonstrated that water based primers (which would be

[15] The state of packaging inks, Flora Davidson, Supply compass, https://supplycompass.com/blog/the-state-of-packaging-inks/ (accessed: 02/18/21)

[13] The state of packaging inks, Flora Davidson, Supply compass, https://supplycompass.com/blog/the-state-of-packaging-inks/ (accessed: 02/18/21)

[14] The state of packaging inks, Flora Davidson, Supply compass, https://supplycompass.com/blog/the-state-of-packaging-inks/ (accessed: 02/18/21)

[15] The state of packaging inks, Flora Davidson, Supply compass, https://supplycompass.com/blog/the-state-of-packaging-inks/ (accessed: 02/18/21)

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applied during the printing process) could be 'broken down' by an alkali solution and more easily removed than standard solvent based primers. As a result, inks printed on the primers could potentially be removed more easily. The REFLEX project also identified a patented technology developed by Cadel Deinking in Spain which can deink surface printed packaging.[16] This technology uses a surfactant in an alkali solution to remove the ink. Small-scale trials with Cadel Deinking demonstrated that it was technically feasible to remove nitrocellulose inks from post-consumer PP and PE flexible packaging and to produce a clear/light coloured recyclate stream.

At the present time it is not economically viable to remove ink during the recycling process (either through using water-based primers during printing or by using an ink removal technology) for post-consumer household films. Unfortunately, the current financial benefit of producing a clear or light coloured recyclate does not compensate for the additional costs involved in the removal of the inks. As the sorting and recycling infrastructure for post-consumer packaging becomes established over the next five to ten years it will be worth revisiting this work and evaluating if ink removal can be commercially viable and consider the environmental impact of the process.[17]

As could be shown both inks and glues do not have any major influence on the circularity of bio-based packaging. Improvements concerning sustainability can be achieved by engineering their type of degradation (biodegradability and enforced degradation in recycling). This is why these components will not be considered in the following chapters. However, they can be of larger interest as the quantity of circular moving packaging increases.

[16] Cadel Deinking, http://cadeldeinking.com/en/

[17] Report on the results and findings from the REFLEX project, Axion Consulting https://ceflex.eu/public_downloads/REFLEX-Summary-report-Final-report-November2016.pdf (accessed: 02/25/21)

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3 Circularity of bio-based packaging

The waste produced by packaging is increasing with the amount of products being shipped worldwide. With growing concerns of the state of the environment, these waste streams need to be considered and optimized to reduce the level of harm these streams have on the environment. One way to evaluate waste streams and its harm on the environment is, by evaluating the end-of-life treatment by using the waste hierarchy (Figure 1). This concept suggests abolishing waste streams (waste prevention, at the top of the pyramid) as the best way to protect the environment. Although this can in some cases be achieved when considering sacrificing packaging for the quality of the product or the ability to use marketing techniques in packaging, the avoidance of packaging is in most cases undesirable. Avoidance is the best solution but not always achievable. It does not meet the objective of this study and is therefore not considered here.

The next best option is the reuse of the products which are considered as waste. This is possible for many (bio-based) packaging products on industrial level (e.g. pallets, boxes, containers) and consumer level (reusable bottles, reusable shopping bags etc.). This of course requires collection and preparation schemes which are linked to infrastructural and consumer behaviour hurdles. Also this requires standards for packaging size, shape and material.

If reuse is not possible, mostly the case because of material abrasion or the described difficulties with required packaging standards, recycling is still a quite sustainable option. This is common practice in plastic and paper packaging and sometimes applied to wood packaging. The recycling is always accompanied by material loss and depending on the recycling type also by quality loss. The recycling into a product with downgraded application is called downcycling. While recycling routes are established for the most common types of plastic, paper and glass recycling is still complicated for most composite materials like combinations of paper, plastic and aluminium packaging for milk and dairy. This will also be discussed more in detail in the upcoming “Recycling” chapter 3.2.

As a last possibility to use waste in a resource-saving way, recovery needs to be considered. If the waste quality is too low or there is no local market for the reuse or recycling of the material, recovery in the form of energy recovery, can be applied. Recovery in some cases can also mean material recovery which is similar to downcycling. One last option for waste to reduce the overall negative environmental impact is the treatment of the packaging materials. This can for example make the waste less toxic for plants, animals and humans. An example might be packaging in the pharmaceutical industry which is linked to toxic waste due to product residues in the packaging which may contain toxic or biologically harmful substances like hormones. The treatment of such waste streams can convert these chemicals into harmless substances. This end-of-life option is not considered in the EU waste hierarchy and will therefore also not be discussed in this study.

This chapter will describe the status-quo of the recycling, reuse and energy recovery of the before mentioned bio-based packaging materials. The most common approaches for the end-of-life treatments of the bio-based packaging materials in the EU are presented. The chapter concludes with official EUROSTAT data on the end-of-life treatment rates for these materials.

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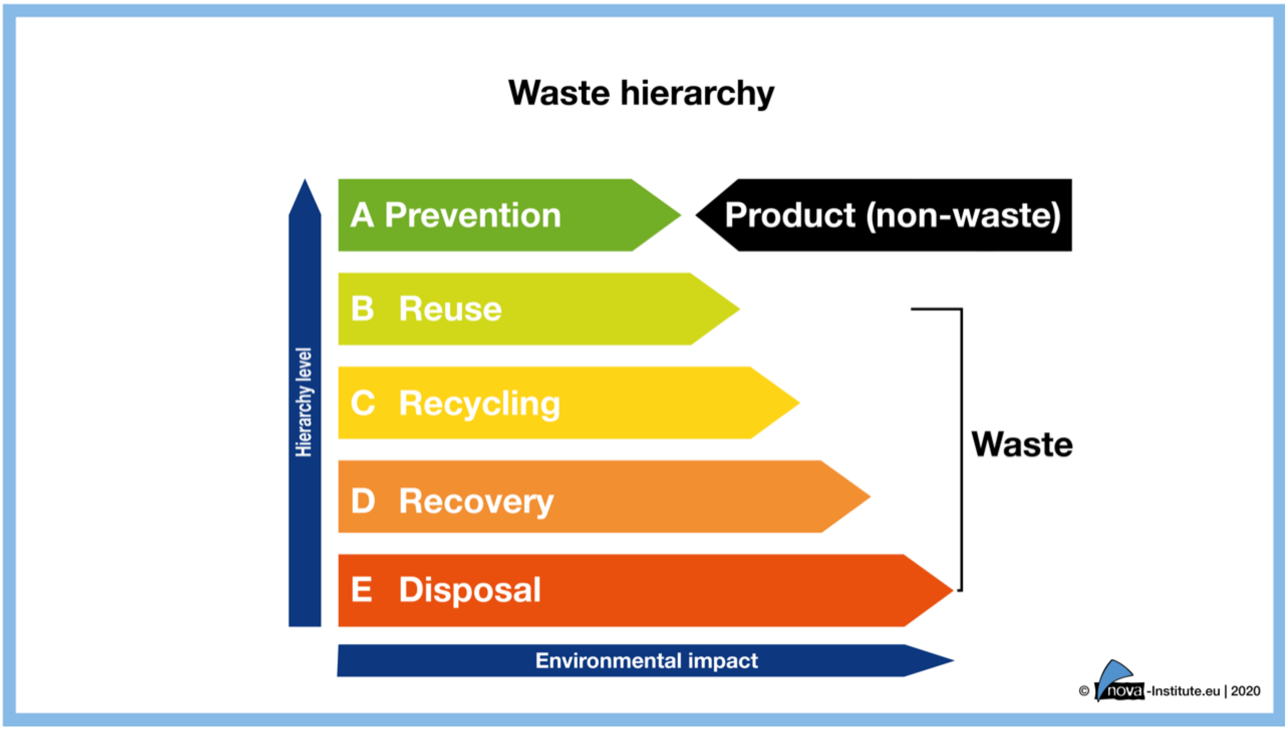

Figure 1: The EU waste hierarchy, which describes the different options for the end-of-life of materials, sorted from most desirable to least desirable. Source: nova-institute 2020, based on https://ec.europa.eu/environment/legal/law/6/pdf/02_aile_eU_waste_legal_framework_speakers_notes.pdf (accessed on 02/25/2021)

3.1 Reuse

In a review of different studies which looked at different packaging types and their influence on the environment, a major part of the studies (76%) pointed to reusable packaging as the most environmentally friendly option. These results, however, are highly dependent on the considerations and assumptions made in each study. This means that decisions on which end-of-life treatment is the most environmentally friendly should be made case-by-case after due consideration has been given to the following parameters which influence the environmental impact:

Influences on the success of reuse systems:

- Materials (quality decrease by time and use)
- Type of return schemes (given infrastructure)
- Standardisation of packaging (usability for different applications)
- Clear communication (comprehensibility by consumer and producer)
- Accessibility of the (alternative) packaging materials

One important finding of the study is, that production and distribution distances are not that influential. The higher the number of cycles, the less significant the production and transport

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distances on the (CO2) impact of the entire life cycle. However, the backhaul and resupply of packaging qualified for reuse between consumer and local markets is more influential on the success of the reuse systems.[18]

Currently the only type of bio-based packaging which is being reused to a high degree is wooden pallets on the industry packaging level. These can be used several times and even be repaired. Frequent users of pallets in some cases create pools of pallets for the shared use and reuse. In the EU the prevalence of multiuse pallets increased from 55% in 2006 to 60% in 2013 and the number of pallets repaired increased from 71 million units to 129 million units in 2013. Other wood-based products like paper & board are currently not being reused due to its short lifetime.[19]

As described in chapter two plastic packaging can be of bio-based origin as well. It is, however, currently not being reused in many applications. On an industrial level plastic pallets are used as alternative to wooden pallets and other boxes and crates can be reused several times before being recycled. On the consumer-level PET bottles might be the best-known example for reuse of plastic packaging. This reuse scheme is well established and reduces recycling and waste of plastic to a high degree. One example for the reuse of bio-based plastics is currently applied by the Coca-Cola company which introduced bio- and recyclate-based PET-bottles called the PlantBottle™. This example combines reuse and recycling of packaging material and is therefore very environmentally friendly.

Applications for composites in packaging are mostly found in milk, dairy and juice packaging. These packaging types show short lifetime and are currently not being reused but increasingly recycled. The recycling of bio-based packaging material is described in the following chapter.

3.2 Recycling

Wood

As already stated above the biggest application for wood packaging is the use of pallets in industrial packaging. After being reused several times wood pallets are mostly collected from companies and then either chipped for uses such as mulch or bedding material in agriculture or in some cases when pallets are chemically treated (often the case in order to prevent insects from habitating in the pallet and spreading to different locations when shipped) or when nails are hard to remove which prevents the chipping, the pallets are used for energy recovery.[20]

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18 Reusable vs single-use packaging: A review of environmental impacts, Zero waste Europe report, https://www.reloopplatform.org/reusable-vs-single-use-packaging-a-review-of-environmental-impacts/ (accessed: 02/11/21)

19 Trends and perspectives for pallets and wooden packaging, United Nations Economic and Social Council, https://unece.org/fileadmin/DAM/timber/meetings/20161018/E/ECE_TIM_2016_6_FINAL_wooden_packaging.pdf (accessed 02/17/2021)

20 Containers and Packaging: Product-Specific Data, United States Environmental Protection Agency https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/containers-and-packaging-product-specific-data (accessed: 02/18/21)

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According to new research conducted by Virginia Tech and the USDA Forest Service, in 2016 the recycling rate of wood was at 95%.[21]

One example for the improvement for wood recycling is the Rilegno consortium which collects wood waste for recycling into particleboard, mdf panels, pulp for paper mills, wood-concrete composites for construction and pallet elements. In order to improve the efficiency of the recycling system following efforts were undertaken:[22]

1.) Rationalization of the logistic chain, that allows for an efficient supply cycle that integrates logistics not exclusively aimed at secondary raw materials collection, which reduces the amount of landfilled waste.

2.) Selection of waste on the basis of its origin and production process, in order to exclude materials containing contaminants of chemical origin used for impregnation, varnishing, treatment.

3.) Management of the materials within the plant through physical separation of different kinds of wood wastes: pallets and packaging, bulky waste, post-consumer wood, manufacturing residues (pre-consumer)

Paper & board

In the EU paper & board is collected separately from other waste streams unless coated with plastic in case of composites. Pure paper and board are recycled by defibrating, diluting the solids of the pulp and cleaning. The cleaning is mostly performed in cascades of filters and separators. By using this approach, paper & board can be recycled up to seven times before the fibres become so small that they disappear from the paper stream into the waste water.[23]

In 2018, approximately 32.1 million tons of corrugated boxes were recycled out of 33.9 million tons of total paper and paperboard recycling. The recycling rate for corrugated boxes was 96.5 percent. After recycling, the combustion of corrugated boxes was 230,000 tons, and landfills received 940,000 tons in 2018. Other pure paper and cardboard packaging, such as cartons, wrapping papers and sacks is mostly recycled as mixed papers.[24]

Plastic

The collection and recycling of bio-based plastic is currently not very developed. Only a few bioplastics are introduced to the market and an even smaller amount is considered for recycling.

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[21] Wood Packaging is Most Recycled Packaging Material, Nature's Packaging https://www.naturespackaging.org/en/why-wood/recycle-reuse/ (accessed: 02/19/21)

[22] Best practices in the wood recycling sector, Case study by Marco Gasperoni, Lead Director of the Rilegno consortium

[23] Adhesives and Tapes Designed to be Less Detrimental to Paper Recycling, Dr. Hermann Onusseit Henkel KGaA Düsseldorf, Germany https://www.adhesives.org/docs/default-document-library/onusseit-henkel-recycliing-wp.pdf?sfvrsn=a13868b8_0 (accessed: 02/19/21)

[24] Molenveld, Karin & Van den Oever, Martien & Bos, Harriëtte. (2015). Biobased Packaging Catalogue.

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This is mainly the case because of missing recycling schemes for certain materials. In some cases this is not a problem as 20% of bio-based plastics are drop-in solutions which are chemical equivalents to their fossil counterparts, mostly PE and PET and can be recycled in the established mechanical recycling systems.[25] Other materials such as PLA have few recycling systems in place, mostly managed by the PLA producers, one example being Looplife from Belgium or Biofutura from the Netherlands. However, it is in some cases like PLA discussed whether or not new bio-based plastics contaminate the established recycling streams, in particular the resulting recyclate and to which extent the blending has no influence on the quality of the recyclate.[26] However, even if bio-based plastics contaminate the recycling stream making the resulting recyclates unusable this can be avoided by improved sorting. The combination of different sorting technologies can separate the most common materials like PET, PE, PP, PS, PVC, PLA, PHB, starch or blends. Common technologies used are near-infrared (NIR), X-ray, colour laser, spectroscopic techniques, screening, wind-sifting, and use of electromagnetism for magnets. Due to little to no recycling of bio-based plastics little is known about the technical qualities of secondary bioplastics after one or more recycling cycles.[27] The end-of-life scenario in which bioplastics are fermented and converted into biogas in conventional anaerobic digestion plants is another possibility which needs further research and optimization before large-scale application can be considered feasible.[28]

Another form of material recycling using physical separation techniques is solvent-based purification or solvolysis. In this process, solvents are used to dissolve plastic waste to selectively purify the target polymer type from the contaminants. Solvent-based purification has been applied successfully for a heterogenous post-consumer PLA waste stream containing ~30% impurities by implementing the CreaSolv® process.[29] In mechanical recycling and solvent-based purification, the polymer composition is not modified.[30]

Chemical recycling, also known as feedstock recovery or tertiary recycling, is a process where plastics are converted into monomers, oligomers or hydrocarbons that can be used again to produce virgin polymers.[31]

Composites

For multilayer packaging basically two kinds of systems are in place which enable recycling. One option is the combined processing of the different components. The other option is to seperate the components by either recycling a target polymer by dissolution and reprecipitation or to seperate the different components by physical or chemical delamination. The mechanism of multilayer

[25] Quelle löschen

[26] End-of-life options for bioplastics, whitepaper by Total Corbion PLA bv, November 2020

[27] Spierling, S.; Knüpffer, E.; Behnsen, H.; Mudersbach, M.; Krieg, H.; Springer, S.; Albrecht, S.; Herrmann, C.; Endres, H.-J. Bio-based plastics—A review of environmental, social and economic impact assessments. *J. Clean. Prod.* **2018**, *185*, 476–491.

[28] Detzel, A.; Kauertz, B.; Derreza-Greeven, C. Study of the Environmental Impacts of Packagings Made of Biodegradable Plastics. 2012.

[29] Fraunhofer Institute for Wood Research Wilhelm-Klauditz-Institut WKI (2017) PLA in the waste stream. https://www.wki.fraunhofer.de/content/dam/wki/en/documents/wki-fachbereiche/hofzet/Results%20summary%20-%20PLA%20in%20the%20Waste%20Stream.pdf (accessed: 02/19/21)

[30] End-of-life options for bioplastics, whitepaper by Total Corbion PLA bv, November 2020

[31] End-of-life options for bioplastics, whitepaper by Total Corbion PLA bv, November 2020

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delamination can be induced physically by the dissolution of macromolecules, and mechanically or chemically by the decomposition of an interlayer or by reactions at the interface.[32]

In either case the recycling system of composites is not very advanced and the situation has only improved for beverage cartons which account for the majority of composite packaging. Currently 25 specialised recycling plants for beverage carton composites are in place in the EU. These recyclers separate the most common composite packaging used for beverages consisting of paper, aluminium and plastic from each other and sell the raw materials for reuse. The paper fibres are used in the paper industry, the plastic (polyethylene) is used in low quality applications like pipes, crates and vessels in the construction industry and the aluminium is used for the production of aluminium foil, pans, buckets and tubes.

Collection and recycling schemes for the different EU countries differ only slightly. In most cases the composite packaging is co-collected with plastic and metal containers. The official material recycling rate of beverage cartons in the EU has increased from 5 % in 1993 to 47 % in 2016. However, environmental NGO's like the DHU in Germany critically review the official recycling data and consider beverage cartons not collected or sorted properly or which are contaminated and therefore burned rather than recycled in their calculations. Their study comes to a reduced material recycling rate for beverage cartons in Germany in 2012 of 36.5 % instead of the official rate of 71 %.[33]

3.3 Recovery

Recovery is the last option with economic benefits due to producing energy or recovering specific materials of a package for downgraded use (which can also be seen as downcycling). Most waste which is collected but cannot be reused or recycled is burned at the recycling plant in order to recover the energy. This is the case for wood, plastic, paper & board and composite packaging. This waste option is however harmful for the environment considering the CO2 footprint and other toxic ingredients produced by burning the carbon-based materials. In some cases, like the Material Circularity Indicator, the resulting CO2 can be part of the calculation when it comes from biological feedstock. This is because in this case used carbon in the feedstock and the produced CO2 from the energy recovery is seen as a part of the biological carbon cycle.

3.4 End-of-life treatment rates

Measuring the circularity of packaging materials is only possible with data for its end-of-life treatments. The end-of-life-treatment rates for the most common packaging materials are gathered in each EU member state and aggregated by the EU department for statistics (EUROSTAT), see Figure 2. Please note that the EUROSTAT numbers only consider the amount of recycling for collected packaging materials, which means that there are discrepancies between the amount of

[32] Recycling of complex packaging materials, Elodie Bugnicourt, IRIS Technology Group, Lorena Rodriguez, AIMPLAS

[33] http://www.allthings.bio/bio-based-beverage-cartons/ (accessed: 02/16/21)

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produced materials to the amount of re-collected materials. Furthermore, such statistics are not available (with some exceptions) for more sophisticated packaging materials like composites or bio-based plastics. This problem will be addressed in chapter 4.4 Replacing missing data.

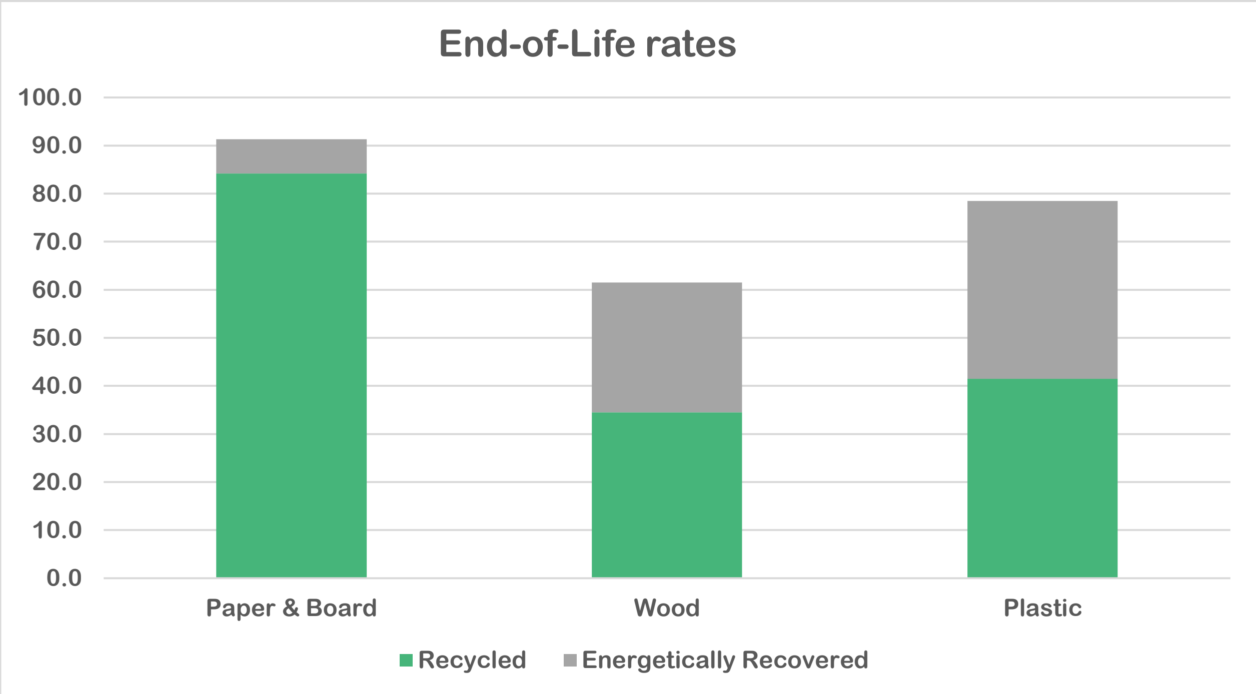

Figure 2: End-of-Life rates, EU average 2018 from EUROSTAT databank.

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4 Methodology

This section describes two indicators which were chosen to measure the circularity of different products and how they are used for specific examples. Moreover, this section analyses the availability of data that is needed for these indicators. The indicators were chosen as they complement each other very well when measuring circularity. While the Biomass Utilization Factor is used for calculating the circularity from a biomass feedstock for the resulting products over several use cycles, the Material Circularity Indicator takes a more detailed approach concerning the product and its components regarding the different sources and types of feedstock, the lifetime and different end-of-life treatments but does not consider further up- and downstream products of the bio-based feedstocks. Both have their pros and cons regarding completeness and applicability of different circular products, which will be discussed in chapter five and six.

4.1 Biomass Utilization Factor

The Biomass utilization Factor (BUF) is used to measure the circularity with a focus on the principle of “keeping materials in use”. This principle describes circularity as a system which introduces as little as possible virgin material into the user market by (re)using it for an extended time and for different applications. This principle builds upon two concepts which are integrated into the BUF-indicator, the “cascading use” and the “production efficiency”. Both are measures which calculate the longevity of biomass material used in different applications and over several use cycles from one product to another. This “waterfall approach” that takes into account several biomass uses in each product stage is called the cascading use of the biomass. The production efficiency accounts for the amount of biomass which is transferred from one usage cycle/ product stage to the next, accounting for material losses through material abrasion, recycling and alternative uses like energy recovery or dumping.

The calculation of the BUF starts at the feedstock level which is referred to stage 0. At this level the biomass input (BI0) is defined as 100% which is why it is accounted with the value 1. From this first stage, the feedstock is distributed to different products and usage purposes in stage 1, which happens by accounting it to different products and usage groups in mass percent of dry biomass. The concept distinguishes in this first step between the use as feed or food, for the production of a product, energy recovery or for other either useful or unuseful manners. In a second step the further distribution of the bio-based content from the product(s) produced in the earlier step is analysed. In this stage 2 the biomass of the bio-based product, can again be attributed to the groups “bio-based products”, “energy recovery” and the “return to the atmosphere” either in a useful or in an unuseful way. Also accounting the share of the bio-based product to the different usage groups. The next stage follows the same procedure distributing the biomass from the bio-based product(s) from the stage before to the different usage groups.

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In order to calculate the BUF the product which is considered and all the by-products produced from the feedstock need to be evaluated from the feedstock level to the end-of-life level. The total BUF is then calculated as the sum of the BUF of each product from each stage. The BUF is equivalent to the amount of biomass which is transferred to the next use stage by using it as a feedstock for a product. As the cycles of use of the biomass are not limited neither is the theoretical total BUF, which makes it hypothetically reach infinite values. To prevent an undefined and growing BUF value, a cut-off event is introduced to the concept which suggests to stop adding further BUF values as soon as either the bio-based product(s) has/ have a value of below 5% or stage 4 is reached.

A more detailed description and visualisation of the BUF is intended to be published as an individual paper in the first half of 2021.[34]

4.2 Material Circularity Indicator

The material circularity indicator is in contrary to the BUF not limited to biomass as a feedstock. This indicator which was developed by the Ellen McArthur Foundation takes into account all feedstock materials and the circularity thereof. "The MCI for a product measures the extent to which linear flow has been minimized and restorative flow maximized for its component materials, and how long and intensively it is used compared to a similar industry-average product." This is accomplished by subtracting the product of the Linear Flow Index (LFI) and a certain function which is dependent of the lifetime of the product and the reduction of virgin raw material use when reused instead of wasted from a base value of one.

In a first step the Linear Flow Index is calculated by taking into account the share of material which is reused, recycled, recovered or used as uncontaminated biomass in contrary to being wasted by landfilling. This indicator considers material waste which originates from the collection, sorting and recycling processes. It also considers sustainably sourced feedstock as reducing factor for the LFI as it is part of the earlier mentioned biological circularity of carbon.

In the picture below the MCI concept is shown briefly. The linear flow can be seen as the sum of the arrows pointing to the right subtracted by the vertical arrows. Flows that contribute to the linear flow are the share of virgin material used for production (V), and the waste streams resulting from post-consumer landfilling, collection or rather rejection from collecting for recycling and waste generated in the recycling process. Flows that reduce the linear flow by improving the circularity are represented by the reused (indexed U), recycled (indexed R) material flow which is collected (C) and prepared to be used as feedstock (F) by a certain mass (M) originating from the considered product.[35]

[34] Carus, M. et al. (2021) nova-paper #14 or 15: Biomass Utilisation Factor (BUF) combines cascading use and production efficiency into one indicator for the circular bioeconomy – to be published 2021, unpublished as of finalisation of this report

[35] Ellen MacArthur Foundation, ANSYS Granta (2019) **Circularity Indicators: An Approach to Measuring Circularity: Methodology**

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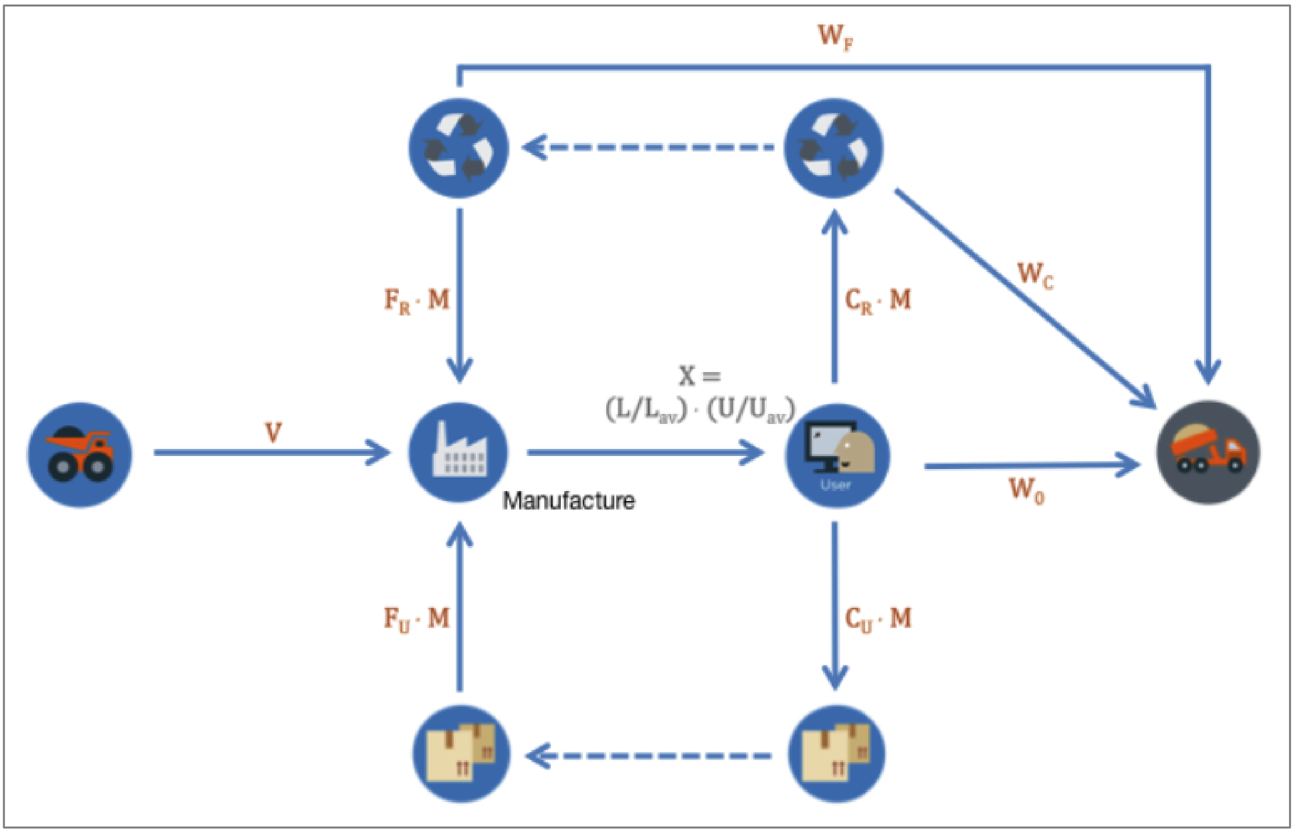

Figure 3: Material Flows relevant for the calculation of the MCI, 2015 version.

The value X denotes the extent to which the product is used as a factor of lifetime (L) and time of usage (U) compared to (divided by) their industry average values (L_{av}, U_{av}). Also, a factor "a" is added to the formula which accounts for the degree of which the improved lifetime and time of usage reduces the need for virgin material. This factor is usually set to 0.9 which sets a range for the MCI value from 0.1 for completely linear materials to 1 for completely circular materials, when considering products with an average lifetime and time of use:

$$MCI = 1 - LFI * \frac{0.9}{X} \qquad \{0.1; 1\}$$

In a newer version of the MCI from 2019, the circular flows are expanded to consider atmospheric equilibrium neutral use of carbon sources. This is done by also considering the use of sustainable material as a Feedstock (F_S) on the input side and the consideration of energy recovery (C_E) and composting of uncontaminated biomass on the output side (C_C). This expansion, however, comes with some limitations that need to be considered when applying these values.
In regard to sustainable materials this comes down to a sustained production in which the extraction of the material:

- is at volumes and practices that maximise the regeneration of natural systems
- does not reduce the capacity for future production of the material
- does not reduce the natural capital associated or dependent on the indigenous ecosystems

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In regard to energy recovery this is limited to:

- Materials for which the only alternative left would be landfilling
- Materials from a biological and demonstrably sustainable production source
- Material which is completely uncontaminated or at least inert and non-toxic
- Material must replace non-renewable alternatives
- By-products must be biologically beneficial

In regard to composting this is limited to:

- Compostable and non-toxic material according to recognised standards
- Biocompatible with the ecosystems to which the compost is introduced to
- By-products must be made biologically available

This expansion is also considered in the case study.

4.3 Data availability & replacing missing data

BUF

For the calculation of the BUF the following data is required:

- Stage 0 Biomass source(s)
- Uses and their share of stage 0 Biomass:
    - Food & Feed
    - Products (considered product and other products from same biomass source)
    - Bioenergy
    - other useful routes back to the biosphere
    - other unuseful routes back to the biosphere
- Reuse and recycling rates for each bio-based product
- Uses and their share of the recycled/ reused biomass:
    - Products
    - Bioenergy
    - Other useful routes back to the biosphere
    - Other unuseful routes back to the biosphere
- Reuse and recycling rates for each bio-based product

The list can be continued in the same way until one of the already mentioned cut-off conditions (stage 4 is reached or the biomass content is below 5 %) takes place. In the actual use case the data should be obtained for a specific product from a specific company. This would require having access to the data of the complete bio-based material composition of each product that results from the feedstock the specific product is made from. It would also require knowing the end-of-life treatment of all of these products produced from the same biomass feedstock and the further use of the biomass which can be reused or is obtained as recyclate from the products originating from the common feedstock. This is impossible with maybe some exceptions in which a biomass feedstock is

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used exclusively for one product and reused for this exact same product over and over. The wooden pallet example described in the next chapter comes close to this state.

If it is not possible to get information on a specific product from a specific company, the next step would be to look at information for product groups in a geographically limited area, e.g. the EU. In this case it is assumed that all composite milk packages are produced from the same share of feedstock sources which result in the same products that are treated the same way at their end of life everywhere in the EU and independent of their producers. This requires data on material composition regarding biomass feedstock, feedstock sources and treatment routes and waste streams for the resulting product groups in a country or on a continent. This method is used for the other two examples considered in chapter five.

If it is still not possible to acquire the needed data further assumptions on the use of the feedstock can be made. One assumption that reduces the amount of data needed significantly is the assumption of single-type-use of the considered biomass. This means that the biomass which is used for the specific product is exclusively used for the production of the considered product and other use groups, but not for other products.

Further assumptions can be made regarding the collection, recycling and recovery rate for different products. This data is neither gathered for each product individually nor for a product group but for material type groups. This might be an unquestionable approach for many but is not that straight forward as it may seem. Concerning the bio-based packaging industry the individual packaging type and their ability to be sorted and recycled correctly is dependent from a range of product and geographic variables like package shape, specific material composition (especially in the case of plastics), amount of recyclate used and return & recycle schemes in the specific region where the package is used.

If there is still data missing another option can be to derive or model the necessary data. This can be accomplished for instance by using data from other countries which have similar agricultural or socio-economic conditions. Also interviewing specialists helped to verify assumptions on, e.g. the significance of glues regarding their circularity, which was said to be not considered significant for the industry.

MCI

For calculating the MCI, the following data is required:

- Input data
  - Amount of virgin material used for the production
  - Amount of recycled material used for the production
  - Amount of reused material used for the production
  - Amount of sustainable material used for the production
- Product longevity
  - Lifetime of the product
- Output data

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  - Amount collected for recycling
  - Amount collected for reuse
  - Amount of carbon used for energy recovery
  - Amount of bio-based material used as uncontaminated compost
  - Amount landfilled
- Efficiencies
  - Collection for recycling efficiency
  - Collection for reuse efficiency
  - Recycling efficiency
  - Energy recovery efficiency

The first and most important information required for the MCI is the material composition of the considered product. The calculation cannot be carried out without sufficient data on the material composition as this is the starting point of the information gathering. Only in very few cases this material composition can be found specifically for the considered product. In all examples the material shares for the packaging product were missing for at least one material type. In some cases, where only few data values were missing these values could be replaced by derivations or actual weighing of the packaging product. Another source used for data on material composition are life-cycle-assessments which in most cases contain a material composition list.

In the following sections it is assumed that a complete material composition list is available. If this is the case but input data is missing the input data can be derived by using material flow diagrams. This was done for the example of the wooden pallet as there is a material flow diagram for wood and paper publicly available.[36] If alternative inputs are possible it is recommended to take a look at the relevant resource prices in the specific country in order to derive the resource input. Moreover, market reports, the OECD website, resourcepanel.org and EUROSTAT Economy-wide material flow accounts (EW-MFA) can help figuring out where the inputs are sourced from. In the case of sustainably sourced materials which is marked green because it was introduced to the MCI concept in the 2019 version the data acquisition can become very difficult. This is the case because the data is linked to several sustainability requirements which need to be fulfilled in order for the material to qualify for being sustainable. For the examples all the bio-based material was considered sustainable. In other cases, this could be determined by taking a look at certificates from the producers concerning the sourcing of different materials. Some examples include the Forest Steward Councilship (FSC) or the International Sustainability & Carbon Certificate (ISCC). In some cases, these certificates can also help by determining the recyclate share used for the production.

Concerning the product longevity empirical data from experienced users can be obtained by interviews, also the warranty of a product might be an indicator for the expected lifetime. Ourworldindata.org offers data on different topics and includes the average lifetime of plastic products.

[36] Mantau, Udo. (2012). **Wood flows in Europe** (EU 27). Project Report, Commissioned by CEPI (Confederation of European Paper Industries) and CEI-Bois (European Confederation of Woodworking Industries).

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Output data is, as already mentioned in the BUF section, mostly not available for specific products because the end-of-life treatment cannot be tracked but for material types. In the examples the data was derived from EUROSTAT which compiles recycling, recovery and landfilling rates for wood, plastic and paper & board packaging for each EU27 country. This of course makes the assumption that bio-based plastic can be equally treated as conventional plastic which is only the case for drop-in solutions. As new types of plastic and new recycling schemes emerge additional data is needed. The amount of product used for energy recovery and composting at its end of life is marked green in the list as it was introduced to the MCI in 2019 as part of the carbon equilibrium extension. It is linked to several requirements that need to be fulfilled in order to account the material to this end-of-life treatment.

The efficiency of the collection (including sorting) and recycling of the material is impossible to determine for specific products and even for product groups or materials as it is dependent on the quality of the collection, sorting and recycling scheme in place. This again is linked to the many different technologies used in these processes. A study on mechanical recycling efficiencies stated that the efficiency for the most common plastic materials is near to 100%.[37] Also, the collection and sorting efficiency is already included in the official EUROSTAT rates. Therefore, the collection and recycling efficiencies were set to one in this case study. The energy recovery efficiency was set to 40% as this is the average efficiency of the steam power engine which is used in recycling facilities.

General

The following diagram shows the amount of data which is needed to calculate the MCI (basic: 2015 version vs. extended: 2019 version including atmospheric equilibrium) and the BUF (basic: up to stage one and extended: up to stage 4). This shows that the BUF needs less data in its basic and single-use-type (only one type of product is produced from the biomass feedstock) version than the MCI but more in its extended version. As mentioned above this does not make any statement about the difficulty of the data acquisition as it might be easier to gather data for the BUF on products of which the recycled material is used for the same product over and over.

[37] Thoden van Velzen E. U., Jansen M., Brouwer M.T., Feil A., Molenveld K. and Pretz T. (2017) **Efficiency Of Recycling Post-Consumer Plastic Packages**, AIP Conference Proceedings 1914, 170002 (2017); https://doi.org/10.1063/1.5016785 Published Online: 12/15/17

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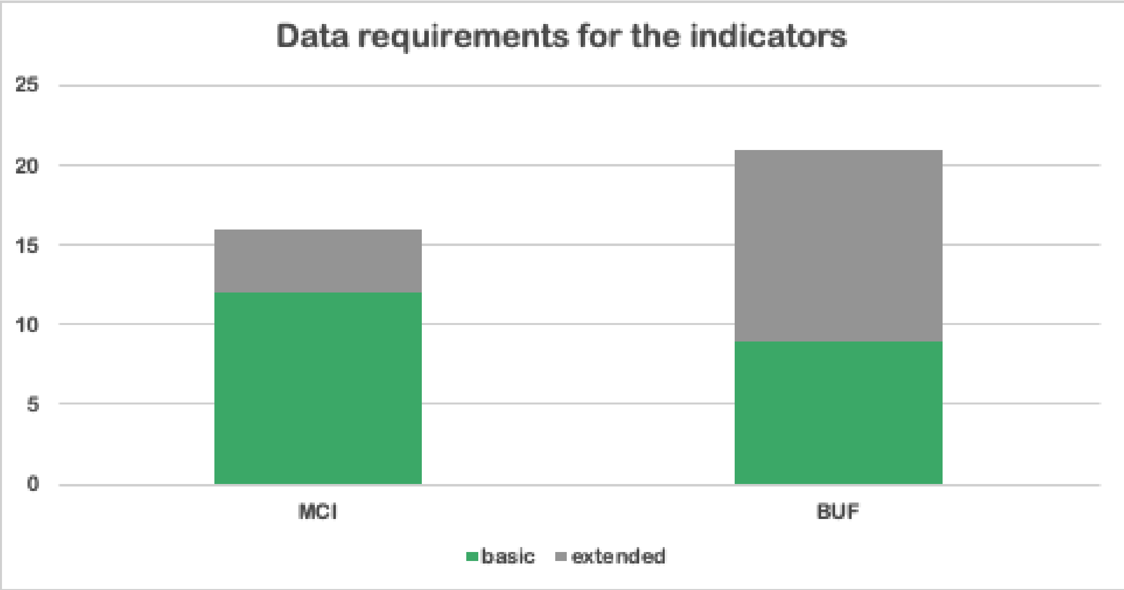

Figure 4: Data requirements for the MCI (basic: traditional & extended: including atmospheric equilibrium) and for the BUF (basic: up to stage 1 & extended: up to stage 4) for a single-use-type biomass.

The data needed in order to calculate the indicators was gathered for specific examples of bio-based packaging. The examples were chosen from EU-based packaging producers which were selected in a first research. Further examples were selected from studies and reviews dealing with the topic of packaging. These were in most cases sustainability reports including LCAs. In general, LCAs offer a good starting point for analysing the circularity of products as they often include a firm material list. From this point it is possible to search for material flow diagrams for the packaging components and recycling, reuse and recovery rates.

Another option to gather information on the used materials and their source is by the producer's website. However, in many cases it was unclear if the information available on the website can be trusted or if it would be considered greenwashing when scientifically analysed. This comes with a lack of trust and little use of established certificates, labels and standardised LCAs. Also, it is mostly not clear whether the products really contain bio-based materials or if these bio-based claims are based on a mass balancing approach allowing for bio-based content to be transferred from one product to another in a certain product group.

Packaging considered is made (at least partly) from the described bio-based materials: wood, paper, bio-based plastic or bio-based composites. A total of 30 packaging products were analysed concerning data availability. Of these only three products qualified for further investigation. Other examples only had less than 30% needed data directly available or at least derivable. This means that basic material quantities of a packaging product are given in order to use this as a starting point and derive the other values by the options mentioned before.

The chosen examples were a wooden pallet, bio-based and recyclate-based plastic packaging for toilet paper and paper/ recycled plastic packaging for dish washer tabs. Even in these cases certain data was missing and needed to be derived or could be requested from the producer.

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4.4 Personal interviews

Personal interviews were the alternative approach aiming towards collecting relevant information on the circularity of packaging. A questionnaire was developed with the intention to cover a number of general questions, some specific questions toward the relevant packaging category, and then a more detailed request on input and output data for a potential packaging product. The full questionnaire can be seen below, highlighted in a contrasting colour:

General:

1. In which sector of bio-based packaging are you active?
    a. Plastics
    b. Paper packaging
    c. Wood packaging
    d. Composite materials
    e. Inks
    f. Glues
2. Where is your company based (HQ)?
3. Where are your main production facilities?
4. How many employees do you have?
5. Which feedstock(s) do you mainly use? Where do you source it?

For plastics:

6. Roughly 20 million tonnes of plastics are produced in Europe for packaging (Plastics Europe, 2019). How large would you estimate is the share of bio-based packaging in Europe?
7. The recycling quota for plastics packaging in Europe is at about 34% (EU-27, 2020, Eurostat). How large do you estimate is the share of bio-based packaging that is recycled?
8. Do you use any kind of recycled material in your material production? If yes, how large is the share? What are the main drivers / obstacles for using recycled materials?

For composite materials:

9. There is no official Eurostat number indicating the recycling quota of “composite material packaging”. Does your branch have any estimations of how large the share is of composite material packaging which is recycled?
10. What are the framework conditions for recycling composite materials? Is it different for various EU countries?

For inks and glues:

11. How large is the market share of bio-based inks / glues used in the packaging sector compared to fossil alternatives?
12. Do your bio-based products advantages / disadvantages for recycling?
13. Does the current political framework support advantageous bio-based solutions that enable better recycling? What would be needed to do so?

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Data collection sheet for your bio-based packaging and selected circularity indicators

General information		
What is your bio-based packaging product?	…	
Typical lifetime of the product?	…	
Which biomass are you using in the product?	…	
Which other materials are required for the product?	…	
Material Input (as dry mass)		
Biomass #1 (please specify here)	??	kg
Other biomass? (please specify here)	??	kg
Virgin / Fossil materials? (please specify here)	??	kg
Reused materials? (please specify here)	??	kg
Recycled materials? (please specify here)	??	kg
Product output		
How much product do you receive from the above input?	??	kg
How much of the biomass input ends up in the product?	??	%
How much of the biomass input ends up as a side-product?	??	%
Can you elaborate how the side-product is used (e.g. for bioenergy, another product?)	…	
How much of the biomass input ends up as a waste? Please specify	??	%
Can you elaborate how the waste is treated (e.g. for bioenergy, incinerated, landfilled)	…	
End of life		
How often is your product reused directly?	??	times
How much of your product is recycled into the same product again?	??	%
How much of your product is recycled into another product?	??	%
How much of your product is utilised for bioenergy at end of life?	??	%
How much of your product is lost to the biosphere / unaccounted for	??	%
How much of your product can be considered as (uncontaminated) biomass at end of life?	??	%

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For the personal interviews, a longlist of potentially relevant actors along the value chains was prepared. Most companies on the list were known to nova-Institute via their business network, allowing for direct communication channels to conduct interviews on the circularity of packaging materials. The following list provides an overview of relevant actors that were contacted among the groups of packaging and of waste management:

- **Paper & Board:** Huhtamaki, UPM, Metsä (Board and Tissue), Stora Enso, Smurfit Kappa, Papier Mettler
- **Glues:** Henkel, AkzoNobel, Nitto Europe, tesa, Kleibereit Klebchemie, Perstorp
- **Plastics:** Braskem, FKuR, Natureworks, Novamont, TotalCorbion, BASF, Neste
- **Composite Materials:** Tetra Pak, Elopak, Smurfit Kappa, SIG-Combibloc
- **Recycles and associations:** Plastics Recycles Europe, bvse, Interseroh, European Bioplastics, European Compost Network ECN, Plastics Europe
- **Wood:** European Federation of Wooden Pellet and Packaging Manufactures FEFPEB, Bundesverband Holzpackmittel HPE, Stora Enso

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5 Calculation & Results

5.1 Data collection

5.1.1 Personal interviews

Altogether, the pathway to collect data via personal interviews did not yield any useful results. Many companies/organisations did respond with interest after initial contact, but regretfully declined to support the approach when the request for specific data became apparent. In the end, a total of four interviews were conducted (due to requests for anonymity, we will not disclose the companies here), where the questions 1–13 of chapter 4.4 were discussed, but no responses on the more specific data request for the data collection sheet could be obtained, even after multiple calls and requests when initial readiness to support the data collection was indicated.

A large reason for the low willingness to conduct the interview was a palpable reluctance to share sensitive data with the project, even when an NDA was proposed and discussed. Here, it seems quite apparent that companies are very cautious to share such information, even when they agreed that such results would be very useful for gaining information on and monitoring bio-based packaging. Another reason that also became apparent was the fact that many companies were either not aware if or did not have at all the data that was requested in order to calculate the two indicators of choice.

That said, some take-aways for the bio-based packaging sectors can still be derived from the interviews, which we want to summarize here:

- For glues in the packaging sector, a bio-based share of 20-30% was estimated
- There is little to no focus and no expectancy on recycling glues in the packaging sector
- Bio-based solutions for glues are more attractive than recycling solutions due to purity reasons
- Main driver for glue selection is that it at least not hinders recycling and in the best case improves recycling – whether the feedstock is bio-based or not is only of secondary importance
- For inks in the packaging sector, a bio-based share of 40-45% was cautiously estimated
- Inks are never entirely bio-based – pigments are never bio-based, while the binder is always colofonium (tree resin)
- Some bio-based ink options like nitrocellulose are bad for food packacking as they cannot be sterilized
- Like for glues, there is indication that bio-based inks are a preferred choice over other inks and there are no political incentives driving or inhibiting bio-based ink demand
- For bio-based plastics, the share in packaging is estimated to be similar to the global share of bio-based plastics

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- For recycling of bio-based plastic packaging, they are coherent with the general plastics recycling in Europe → large streams like PE are recycled, which means that bio-based PE is recycled as well.
- Chemical recycling, e.g. solvent-based, was suggested as a potentially very interesting solution to increase recycling shares.
- EUROSTAT was mentioned to become more and more aggregated, which is counterproductive for focused monitoring of the bioeconomy

5.1.2 Literature and statistics

Compared to the difficulties through the personal interviews, official statistics plus deeper digging into literature led to some results that could be used for calculating the two circularity indicators. That said, official statistics (in particular EUROSTAT) aggregate statistical data usually on a higher level than what would be necessary for the calculation of the indicators. As a consequence, the three in the following introduced examples are largely based on additional literature information that was identified outside of official statistics, and then, in order to enable a calculation of the circularity indicator, some information from official statistics were added or used as assumptions to close existent gaps. For more details, please refer to the three following examples in chapter 5.2.

5.2 Example 1: Wood packaging

A wooden EURO pallet is used as an example for industrial packaging. Mass and material composition are average values obtained from a Review of LCAs for wooden and plastic pallets.[38]

MCI

For the calculation of the MCI the average mass of a EURO pallet and the average mass share of the iron nails is considered. The wood for the pallet is in this case exclusively sourced sustainably. The lifetime is considered being 14 use cycles which is the standard lifetime of a wooden pallet. The complete pallet (excluding the nails) is used for energy recovery at its end of life. As only the carbon share can be considered for circular energy recovery, the carbon share had to be determined, in this case to a value of 50%, following the suggestion on the Wikipedia article for the carbon content of wood. The energy efficiency is set to 40% which is the value for average steam power engines used for energy recovery in the waste industry. By calculating the MCI from these numbers this results in a value of 0.63 for the MCI.

Table 1: Calculation of the MCI for a wooden EURO pallet.

Data type	Assumption/ Derivation	Value
Mass of the product (kg)	Average EURO pallet	21.82
Virgin Material (kg)	Only nails (iron)	0.38

[38] Deviatkin I, Khan M, Ernst E, Horttanainen M. Wooden and Plastic Pallets: A Review of Life Cycle Assessment (LCA) Studies. *Sustainability*. 2019; 11(20):5750. https://doi.org/10.3390/su11205750

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Recycled Feedstock (%)	-	0.00
Feedstock efficiency (% recyclate produced)	-	-
Reused Feedstock (%)	-	0.00
Sustainable Feedstock (%)	Sustainably sourced	1.00
Collected for recycling (%)	-	0.00
Collection efficiency (%)	-	-
Collected for reuse (%)	-	0.00
Collected as un-contaminated biomass (%)	-	0.00
Collected for energy recovery (%)	Carbon content: 50 wt% Energy efficiency: 40%	0.20
Lifetime (use cycles)	Average lifetime	17.00
Industry-average Lifetime (use cycles)	-	17.00
Waste from collecting for recycling (kg)	-	0.00
Waste from recycling for feedstock (kg)	-	0.00
Total waste (kg)	-	17.53
Linear Flow Index	-	0.41
Utility Factor	-	1.00
A	-	0.90
MCI	-	**0.63**

BUF

The wooden pallet is made from only one type of biomass, which is wood. A material flow diagram for wood streams in the EU was used for deriving the relevant numbers in each stage.[39]

In a first step (stage 1) the wood results in two intermediate products (pulp and wood workpieces) and in bioenergy. From the wood production the wood streams are directed either to the production of wood products (in this case the pallet) and in case of residues towards use in pulp production, other wood-based production and bioenergy, this is stage 2. In the other stage 2 process, the pulp production the resulting streams are directed either towards paper production or towards bioenergy (residues). In stage three, the end of the lifetime of the considered pallet, four different products are obtained from the products of stage 2: Paper, recycled paper, wood products and pulp. The major stream however originates from the end of life of the pallets into carbon sequestration, which is in this case considered as “back to the biosphere, unuseful”. In the last stage, stage 4, (recycled) paper is obtained as only product. Without the cut-off condition defined in the BUF concept this (recycled) paper would be considered in further stages as its raw materials can be reused until the lignin fibres get too small. Waste streams originating from the paper production or paper recycling end up being incinerated, landfilled or in the form of carbon sequestration.

By adding up the share of usefully deployed biomass in each stage for each product, the biomass utilization factor of this stage is obtained. The sum of these stage-specific biomass utilization factors is the overall BUF of this product.

[39] Mantau, Udo. (2012). **Wood flows in Europe** (EU 27). Project Report, Commissioned by CEPI (Confederation of European Paper Industries) and CEI-Bois (European Confederation of Woodworking Industries).

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Table 2: Calculation of the BUF for the wooden EURO pallet.

Data type	Assumption/ Derivation	Value
Stage 0: **BUF0**	wood	**100% of investigated biomass**
Stage 1:		
Food & Feed	-	0.00
Bio-based products	Wood components & pulp	0.64
Bioenergy	-	0.36
Back to biosphere useful	-	0.00
BUF 1	-	**1.00**
Stage 2:		
Bio-based products	Wood products, paper & industrial residues	0.59
Bioenergy	-	0.05
Back to biosphere useful	-	0.00
BUF 2	-	**0.64**
Stage 3:		
Bio-based products	Wood components, paper & pulp	0.17
Bioenergy	-	0.18
Back to biosphere useful	-	0.00
BUF 3	-	**0.35**
Stage 4:		
Bio-based products	Industrial residues, wood products & paper	0.16
Bioenergy	-	0.00
Back to biosphere useful	-	0.00
BUF 4	-	**0.16**
Total BUF		**2.15**

5.3 Example 2: Bio-based plastic packaging

In this example the MCI and the BUF are calculated for plastic packaging of toilet paper which is assumed to be 50% from recycled plastic and 50% from bio-based polyethylene.

MCI

For the input the mass of the product is estimated, the feedstock efficiency is ignored and set to 1 and the bio-based PE is assumed to be sustainably sourced. The lifetime of the product is assumed to be the industry average. For the output side recycling, landfilling and energy recovery rates are obtained from EUROSTAT. The carbon content from polyethylene is used for the complete product and the energy efficiency of the recovery is set to 40% which is the average efficiency of steam power engines used at waste processors.

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Table 3: Calculation of the MCI for the bio-based plastic packaging.

Data type	Assumption/ Derivation	Value
Mass of the product (kg)	Assumption	0.05
Virgin Material (kg)	-	0.00
Recycled Feedstock (%)	Based on EUROSTAT recycling rates (so likely overestimated)	0.50
Feedstock efficiency (%)	Assumption	1.00
Reused Feedstock (%)	-	0.00
Sustainable Feedstock (%)	Assumption: Sustainably sourced	0.50
Collected for recycling (%)	Source: EUROSTAT	0.31
Collection efficiency (%)	Assumption	1.00
Collected for reuse (%)	-	0.00
Collected as uncontaminated biomass (%)	-	0.00
Collected for energy recovery (%)	Assumption: carbon content for package equals carbon content of PE: 85% Energy efficiency: 40%	0.01
Lifetime (use cycles)	Average lifetime	1.00
Industry-average Lifetime (use cycles)	-	1.00
Waste from collecting for recycling (kg)	-	0.00
Waste from recycling for feedstock (kg)	-	0.00
Total waste (kg)	-	0.03
Linear Flow Index	-	0.33
Utility Factor	-	1.00
a	-	0.90
MCI		**0.69**

BUF

In this case it is assumed that the bio-based polyethylene is sourced from sugar cane which is converted into ethanol and then into ethylene monomers. Important by-products of this process are bagasse, vinasse and CO_2. Bagasse is the lignin-based wood-like fibre material which is in many cases used for bioenergy. Vinasse is a liquid which contains the bio-chemical components which are not necessary for the polyethylene production. This by-product is mostly considered as waste because it can be harmful for the environment when disposed in high amounts. However, it can also be used as a replacement of chemical fertilizers, as could be shown in a study from the National Research Centre in Cairo, Egypt.[40] This application for vinasse is assumed in this study. After the end of life of the plastic packaging the material is recycled and reused partly for the same application.

[40] Abd el halim Mahmoud, S., Salah Siam, H., Said Taalab, A., Mahamed El-Ashry, S., 2019, “Significant use of vinasse as a partial replacement with chemical fertilizers sources for spinach and barley production and their effect on growth and nutrients composition of plant” Plant Archives Vol. 19 No. 1, pp. 1593-1600

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Table 4: Calculation of the BUF for the bio-based plastic packaging.

Data type	Assumption/ Derivation	Value
Stage 0: **BUF0**	Sugar cane	**100% of investigated biomass**
Stage 1:	-	
Food & Feed	In this case not used for food/ feed	0.00
Bio-based products	Ethanol	0.06
Bioenergy	Bagasse	0.21
Back to biosphere useful	Vinasse	0.67
BUF 1	-	**0.73**
Stage 2:		
Bio-based products	50% conversion rate from ethanol to PE	0.03
Bioenergy	-	0.00
Back to biosphere useful	-	0.00
BUF 2	-	**0.03**
Stage 3:		
Bio-based products	Recycled PE, EUROSTAT recycling rate for plastic in the EU: 31%	0.01
Bioenergy	PE used for energy recovery, EUROSTAT EU-average rate: 67%	0.02
Back to biosphere useful	-	0.00
BUF 3		**0.03**
Stage 4:		
Bio-based products	Recycled PE, EUROSTAT recycling rate for plastic in the EU: 31%	<0.00
Bioenergy	PE used for energy recovery, EUROSTAT EU-average rate: 67%	0.01
Back to biosphere useful	-	0.00
BUF 4	-	**0.01**
Total BUF	-	**0.79**

5.4 Example 3: Paper / recycled plastic packaging

For this example, packaging for dishwasher tabs was analysed. The individual tab is wrapped in plastic which is from 50% recycled sources. The secondary packaging the box in which these tabs are contained is made from paperboard.

MCI

The mass of the total product (primary & secondary packaging) is estimated to be 100g of which 10g is accounted to the shrink film wrapping of each individual dish washer tab and 90g are accounted to the secondary paperboard packaging. The feedstock efficiency for the recycled plastic is assumed to be one and the wood for the paperboard is assumed to be sustainably sourced. The

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collection efficiency is assumed to be one as it is already accounted for in the collection rate from EUROSTAT. The carbon content for paper is assumed to be 27% and for polyethylene 86%. The energy efficiency is estimated to be 40% which is the average efficiency of steam engine power plants.

Table 5: Calculation of the MCI for the paper and plastic dishwasher tab packaging.

Data type	Assumption/ Derivation	Value
Mass of the product (kg)	-	0.10
Virgin Material (kg)	-	0.01
Recycled Feedstock (%)	50% of the plastic used for the primary packaging	0.05
Feedstock efficiency (%)	Assumption	1.00
Reused Feedstock (%)	-	0.00
Sustainable Feedstock (%)	Wood for paper is sustainably sourced	0.90
Collected for recycling (%)	EUROSTAT: paper & board: 84%, plastic: 41,5%	0.78
Collection efficiency (%)	assumption	1.00
Collected for reuse (%)	-	0.00
Collected as uncontaminated biomass (%)	-	0.00
Collected for energy recovery (%)	Carbon content: Paper: 27%, PE: 86% Energy efficiency: 40%	0.02
Lifetime (use cycles)	Single use product	1.00
Industry-average Lifetime (use cycles)	Single use product	1.00
Waste from collecting for recycling (kg)	-	0.00
Waste from recycling for feedstock (kg)	-	0.00
Total waste (kg)	-	0.02
Linear Flow Index	-	0.13
Utility Factor	-	1.00
a	-	0.90
MCI		**0.89**

BUF

As the only bio-based packaging material is in this case paperboard and paperboard is produced from wood just as the wooden pallet from example one, the same data source (material flow diagram for wood) can be used for this packaging type.[41] Which comes to a BUF value of 2.16. The following values are for a case in which all the available wood is used for paper production and bioenergy and there is no share used for wood production. This will show a further example resulting in another BUF value for comparison.

[41] Mantau, Udo. (2012). **Wood flows in Europe** (EU 27). Project Report, Commissioned by CEPI (Confederation of European Paper Industries) and CEI-Bois (European Confederation of Woodworking Industries).

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Table 6: Calculation of the BUF for the paper & plastic (not considered here) packaging of dish washer tabs.

Data type	Assumption/ Derivation	Value
Stage 0: **BUF**	wood	**100% of investigated biomass**
Stage 1:		
Food & Feed	-	0.00
Bio-based products	Pulp	0.64
Bioenergy	-	0.36
Back to biosphere useful	-	0.00
BUF 1		**1.00**
Stage 2:		
Bio-based products	Paper	0.41
Bioenergy	-	0.27
Back to biosphere useful	-	0.00
BUF 2		**0.68**
Stage 3:		
Bio-based products	Recycled Paper	0.28
Bioenergy	-	0.00
Back to biosphere useful	-	0.00
BUF 3		**0.28**
Stage 4:		
Bio-based products	Recycled Paper	0.20
Bioenergy	-	0.00
Back to biosphere useful	-	0.00
BUF 4		**0.20**
Total BUF		**2.16**

5.5 Comparison & Scenario Analysis

MCI

The values for the MCI in the different cases range from 0.63 (wood pallet) and 0.69 (bio-based plastic packaging for toilet paper) to 0.89 (plastic/paper dishwasher tab packaging) which are all moderate values as the MCI can take values from 0.1 to 1 with one accounting for a fully circular product. One would expect the wood pallet to be more sustainable because of its reuse over several cycles and the completely bio-based source (except the small amount of nails). However, this is not the case as this indicator does not monitor sustainability and does not favour bio-based content to other reused content. Also, the several cycles of use that increase the lifetime of the product are not brought in comparison to other products in the MCI but only to lifetimes of the same product (industry average lifetime of the same product). This makes it difficult to compare different products at least when considering their lifetimes. This problem could be solved when using industry average lifetimes of bigger product categories like in this case the packaging industry. Also, the slightly lower value of the wood pallet can be explained by the accurate calculation of the energy recovery which only considers the carbon content and only to a degree of actual efficiency. The average content was found to be 50 wt% and the efficiency 40%. This means that only 20% of the mass that is used for energy recovery is considered being used in a circular way. If the wood of the pallet would

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instead be used for another product the MCI would be higher. This is shown in Figure 5 (extended use of the pallet in grey) where the pallet is reused as chipped wood in the agricultural sector.

All values would be lower if the feedstocks were not sustainably sourced which is assumed in this study but not always given for granted. This depends on the sustainability criteria.[42]

Overall the MCI can be described as being a good indicator for quantifying the circular equilibrium of all materials on an economic level and, with the extension of the 2019 version, the circular carbon equilibrium on a biosphere level. The MCI is not useful when comparing different products with different lifetimes. It also has further drawbacks as certain values are very complicated to estimate or derive, such as the feedstock efficiency and some values are linked to several requirements that need to be checked for (e.g. sustainability requirements for sustainable feedstock or carbon content and energy efficiency for energy recovery).

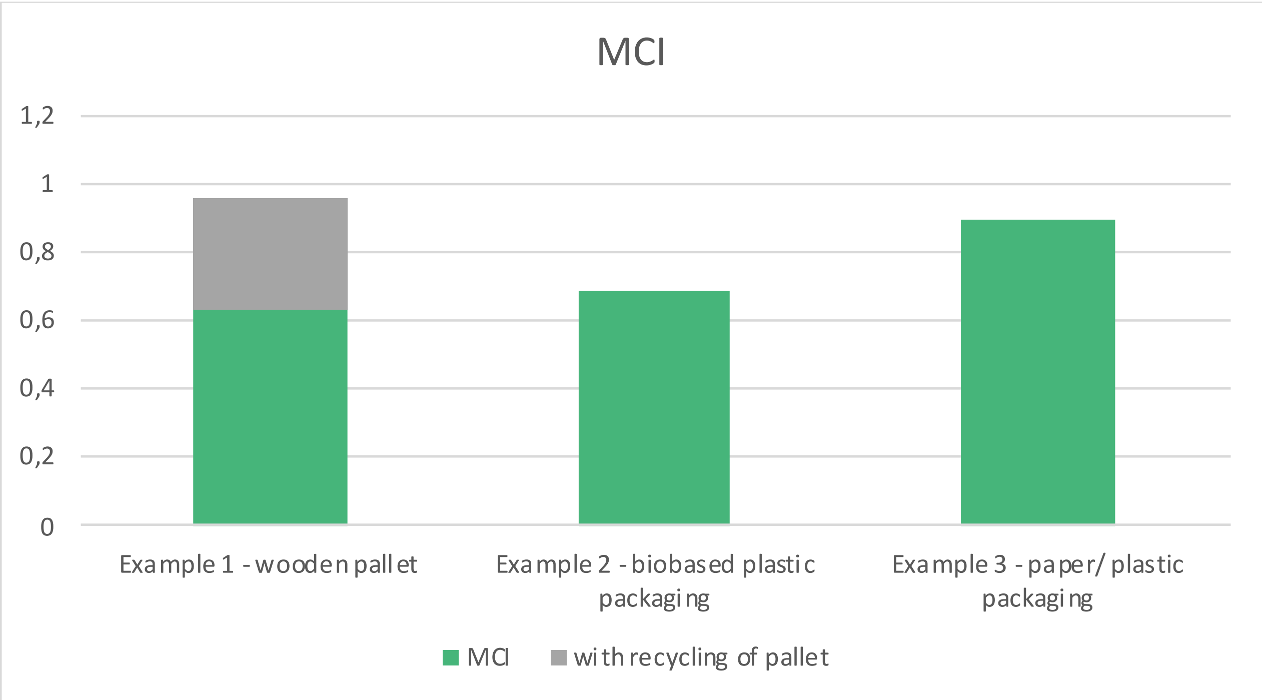

Figure 5: Results for the calculation of the MCI for the examples.

BUF

The BUF takes values from 0.79 (bio-based plastic toilet paper packaging) to 2.15 (wood pallet) and 2.16 (plastic/ paper dishwasher tab packaging). As the BUF only considers the bio-based material share the two streams wood biomass (for pallets and the paperboard for the secondary packaging of the dishwasher tabs) and sugar cane are considered in these examples. For the wood pallet

[42] Ellen MacArthur Foundation, ANSYS Granta (2019) **Circularity Indicators: An Approach to Measuring Circularity: Methodology**

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information on the material streams for wood were taken from a publicly available material flow diagram for wood in the EU. The same source was used for the calculation of the BUF in the case of the paperboard packaging for the dishwasher tabs but with the assumption that the wood is sourced solely for bioenergy use and pulp production. The information on the material flow of sugar cane was taken from a publicly available education website. What was striking when calculating the BUF was the large amount of information needed for bio-based supply chains which was already described in the chapter data availability. In the case of wood as a feedstock this was possible thanks to the material flow diagram. In the case of the bio-based PE this was more complicated and the end uses for different by-products had to be guessed.

The results show two important implications. Even though in the case of wood pallets the wood is first used as wooden product and then used for paper production which would make one think that this value would be higher when compared to the material flow considered for paper production which does not consider wood being used for wooden products but only for bioenergy or the pulp production. This is however not the case because on the one hand the material flow diagram suggests that a lot of wooden products are left for carbon sequestration at their end of life instead of being used for the production of paper or burned for energy recovery. And, on the other hand does the BUF not account for the lifetime of the products which is much higher for the wooden products compared to the paper products. This was also the case with the MCI which did consider the lifetime of the products but only compared it to the industry average of the same product class. This problem is faced by both indicators.

The value of a specific product is strongly dependent from the utilization of the biomass it is produced from but less so from the circularity of the specific product. This is already shown by the name of the indicators but should be reconsidered at this point as this is a study analysing the circularity of different packaging products. Even though the bio-based plastic is a drop-in solution which can be handled in the traditional mechanical recycling systems it does not come close to the wood-based products because the sugar cane biomass can only be used over and over again to a small amount. In the scenario analysis another use for the bagasse and the produced CO_2 is considered which increases the BUF value and thereby shows that more efficiency of the use of the biomass results in higher BUF values. This is definitely an interesting incentive for the industry (to increase the utility of the biomass) but reduces the overall significance of the indicator regarding the monitoring of the circularity of specific products.

Overall the BUF can be described as being especially helpful for considering and incentivizing the useful consumption of all parts of the biomass used for a product which is for what it was developed. By this it not only considers one single cycle of a material but its uses over and over which helps especially when considering valuable resources being used for the growing or sourcing of specific materials because it offers an extended calculation of the circularity by the principle “keep materials in use”. It also accounts for the number of applications from a single feedstock respecting waste production in the sourcing and processing of specific materials. On the other hand, it does not account for the time of use/ lifetime which makes the comparison of products with different lifetimes complicated. It also only accounts for the bio-based part of materials not considering the circularity of other materials used in the product. One last drawback is the high amount of information needed as the calculation starts with the sourcing from the raw material and considers

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all products used from this feedstock. This is necessary to give a wholesome picture of the usefulness and a more wholesome picture on the complete circularity which might be desired for certain decision-makers, especially in the case of efficient land-use for bio-based materials but could be too complicated for companies when wanting to compare two products regarding their circularity.

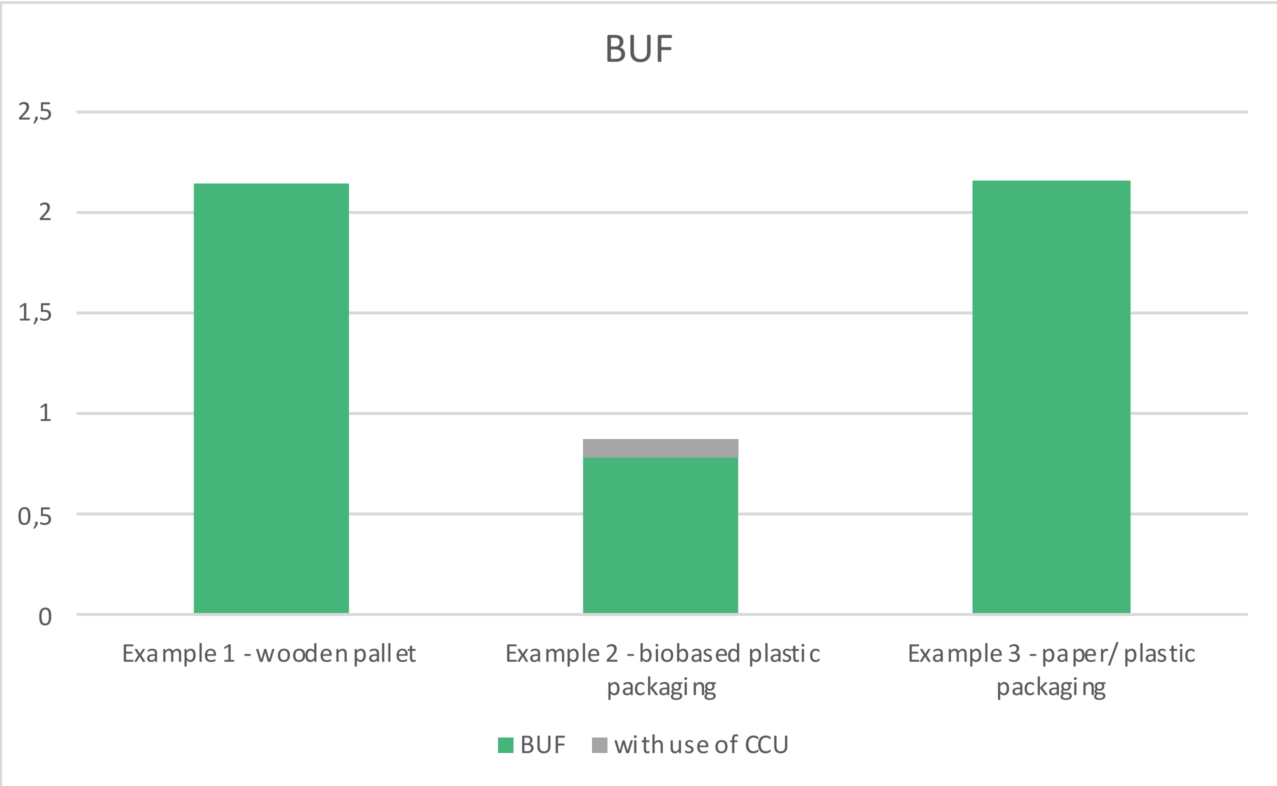

Figure 6: Results for the calculation of the BUF for the examples.

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6 Conclusion

This study aimed at giving an overview on investigating a monitoring of the bio-based packaging industry in the EU. The relevant materials were described in chapter two. These are wood, bio-based plastic, paper & board, bio-based composites as well as bio-based glues and inks. While wood and paper packaging materials are almost exclusively produced from one raw material bio-based plastic and composites can be made of different bio-based feedstocks and in different compositions and types. This opens up many possibilities for the use of bio-based feedstocks in many industries including the packaging industry. However, the different compositions and types of material can be limiting for the sorting and recycling process at the end of life.

The end of life treatment of the different materials is considered in chapter three. Here, it is stated that a lot of packaging is not regularly reused (with exceptions being wooden industrial packaging like pallets, boxes and crates and the bio-based PET PlantBottles™). Most bio-based materials are however being recycled with EU average recycling rates ranging from 35% (wood) and 42% (plastic) to 85% (paper & board). Please note that this value is only true for the amount of collected materials. Recycled plastic is commonly downcycled, at least in a quality sense, and the recyclate used for lower quality products in the next cycle. Wood is in most cases recycled to be reused as sawnwood for the wood industry, in the form of chipped wood for the agricultural industry and as raw material for the production of paper. Paper & board is collected separately and recycled to be used again as recycled paper. All packaging products that are collected but cannot be recycled or reused are burned for energy recovery.

In chapter four the circularity of the bio-based packaging industry was analysed on a quantitative level using two circularity indicators, the Biomass Utilization Factor and the Material Circularity Indicator. Both indicators describe the circularity of materials used in (packaging) products. The BUF concentrates on the bio-based materials while the MCI also considers other materials. The BUF regards the different applications of biomass starting at the sourcing of the material. It thereby considers the entire supply chain of the relevant product and all the co-products. This helps analysing the utilization of bio-based materials in order to prevent wasteful use. It is especially useful for cases of scarce land availability and the use of precious raw materials. However, as it indicates the utilization of the biomass for all products sourced from this bio-based material a lot of information on the supply chains for each product is necessary. Here, the collection of the necessary data appears to be a larger issue. Within this case study, two approaches were conducted. The first approach via personal interviews yielded rather disappointing results with only a low willingness of companies to support such a (sensitive) data collection. The other approach, focussing on statistics and available literature resources, yielded better results, but still has to work with assumptions to cover data gaps. We assume that in many cases the required information can only be accessed by direct contact to the value chain actors. In order to be used in a generalised way for the Biomonitor project and in the perspective of a modeling for the bioeconomy, improvements in the formal collection of such information would go a long way. The examples showed that, if the needed information is available, useful results for comparing the circularity of different products and their bio-based raw materials can be achieved.

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The MCI does not focus on specific (bio-based) material but instead considers all used materials in a product when indicating its circular use. This indicator focuses on the linear versus circular use of materials and, in the updated 2019 version, also on the overall influence on the carbon equilibrium in the biosphere. This means that it measures the linear flow of materials (from virgin feedstock to landfilling), the lower the linear flow the higher the circular flow of these materials (reuse, recycling). It also considers (under certain conditions) sustainably sourced virgin material, energy recovery and the uncontaminated composting as circular material flow as this does not change the carbon equilibrium in the biosphere. It also considers the lifetime of a product compared to the industry average of this product class when calculating the MCI. Most problematic concerning the data acquisition is the access to product-specific information on lifetime and information making statements on the requirements for the "expanded circularity". In the case of lifetime user experience might help making assumptions. In the case of sustainability requirements, it might help to look out for sustainability certificates in regards to the sourced materials and for toxic or environmentally harmful materials or additives in regards to the ability of carbon neutral end-of-life treatments. The examples showed that the MCI focusses strictly on the circularity of the materials (or carbon in case of the extension) used in a product and does not consider further sustainability values. The comparability of different products is also limited by the narrow calculation of the lifetime which results in a "product class"-specific value. The big impact of increased circularity on the overall MCI value was showed when the wooden pallet was not considered being burned for energy recovery at its end of life but being recycled for use as chipped wood mulch in the agricultural sector. This increased the resulting MCI from a value of 0.63 by 52% to 0.96.

In conclusion, it can be stated that both indicators qualify for their use in the Biomonitor project as they account for the circularity of materials which preserves the environment by reducing environmentally harmful sourcing and reducing land use. Both outcomes can be seen as necessary objectives when transitioning to a bio-based economy. To monitor the circularity the relevant data inputs for the indicators need to be available on a regular basis for different regions and different applications. This goal can only be accomplished with the collaborative support from the agricultural and biomass processing sector and other material intensive industries in the EU member states, in order to fill data gaps. Some recommendations for developing a broad database are given in the following chapter.

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7 Outlook & Limitations

This chapter shows different possibilities for further developments in the area of circularity and its measurement. It thereby first addresses the limits of data availability which can be seen as source of the communication problem in the supply chain of reused and recycled products. In a next step the limits of the indicators and their ability to monitor the circularity are described and possibilities for improvement given.

Data availability & communication

Data availability and communication can be seen as the major problems when measuring and improving the circularity of (bio-based packaging) products. The lack of communication reaches from the sourcing of (bio-based) materials to the consumer and the recycling companies. This has several reasons like a fear of competition because the material might be considered to have lower quality. Also, the consumer knowledge on sustainability and circularity is scarce, which is why the demand for environmentally-friendly products is low. This lack of communication and cooperation is especially problematic between manufacturers, sorting centres and recyclers because it makes it difficult to keep up with sorting and recycling activities for new materials. Also, when communication and cooperation among manufacturers from different sectors is lacking opportunities on standardising the composition of materials in order to improve sorting and recyclability are missed out on and the use of recyclates decreases. In the bigger picture the lack of communication restricts the efficient allocation of resources. Manufacturers are not informed about availability and applicability of recyclates for their products which drives the sourcing of virgin materials. Consumers are not informed about sustainability of the products and their influence on the environment, which does not incentivize sustainable consumption. Recyclers are not informed on material composition of the products in use, which makes it difficult to predict recyclate streams in order to sell these to manufacturers at an adequate price.

This communication problem can also be described as a problem of data availability. Where the supply chain participants are not willing to communicate there is no available data. However, this lack of data could be removed by implementing an interactive databank which tracks, calculates and predicts material streams based on the sourcing and manufacturing of products. By making the data anonymous the information cannot be linked to a specific company and generate bad publicity for the company or their products. This would improve the competition by incentivizing manufacturers to adapt their production processes to reuse and recyclate streams as these might be cheaper than sourcing virgin material. This would also help develop improved collection and recycling schemes for better circularity as the collectors and recyclers can foresee upcoming waste streams and prepare their technological equipment and infrastructure. This would reduce collection and recycling costs as these activities could only be carried out when necessary thereby reducing labor, energy and overall operating costs. It would drive the material industry towards a new, more automated and demand-driven industry with less overproduction and waste streams and ideally more circular use.

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Further possibilities to track materials and improve recycling are in development. As for example the technology currently developed from BASF and Security Matters which uses a unique and unalterable chemical-based barcode that withstand manufacturing and mechanical recycling processes without altering the appearance or performance of the object. This barcode can capture a wide variety of information in order to improve collecting, sorting and recycling.[43]

Indicators

Although the indicators qualify for the monitoring of circularity they have several drawbacks that should be considered. First of all it must be stated that these indicators focus on the circularity of (bio-based) materials and do not account for other sustainability measurements like CO2 production, water use, energy use or material scarcity. These additional measurements might in case of the MCI be added to the calculation in several ways which are described in the MCI Paper. When regarding sustainability issues these indicators can offer a glimpse on one aspect of sustainability but cannot be considered sufficient for the overall assessment. It is therefore advised to additionally regard further instruments like LCAs to evaluate the sustainability of certain materials and products.
Another aspect which is limiting in both cases is the amount of required data. Even if such databanks as described before additional data would be required for some specific cases. In regards of the MCI this is especially true when considering the updated 2019 version which needs data on the sustainability of material sourcing, carbon content, toxic and environmentally harmful ingredients and efficiency of energy recovery. Some helpful information might be obtained from certificates for materials and products, such as certificates for sustainably sourced wood (e.g. FSC or PEFC).
One last disadvantage of these indicators is that closed loops, although preferable from a circular view are not favoured by the indicators. Closed loops reduce (environmental and monetary) costs by reducing transport and waste from overproduction or lack of demand for a specific recyclate.
These limits can be seen as small obstacles on a path to the implementation of a circularity monitoring system which can easily be overcome by additional advancements. In many cases, as was seen by the examples, the MCI and BUF can be seen as helpful tools for indicating the circularity of materials and products.

Indicators

Future policy might be an important factor for the bioeconomy as a whole and for bio-based materials in the packaging sector in particular. With the European Green Deal, the European Union has presented a plan to make the economy of the EU sustainable. In the light of the Green Deal, the Circular Economy Action Plan was also updated and includes the packaging sector as one of its key value chains. Finally, plastics is another key value chain and in light of the EU plastics strategy, the so-called Single-Use Plastics Directive might be a driver in favour of bio-based packaging materials, as “natural polymers” are exempt from the restriction imposed on certain products by the directive.

[43] BASF Partners to Accelerate Circular Plastics, by Axel Barrett, 4/20/20 https://bioplasticsnews.com/2020/04/20/basf-partners-security-matters-accelerate-circular-plastics/ (accessed: 03/04/21)

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