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Making materials for packaging circularity

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Abstract: Circular packaging materials are becoming increasingly relevant to ensure sustainable and environmentally friendly solutions for citizens and future generations. This work aims to present a glimpse of the current state of research by analysing fifty relevant case studies of packaging materials on the market or under development (for food, disposables, cosmetics, luxury, electronics, healthcare, etc.). The conducted analysis and clustering activity pointed out prominent development trends for incoming years. The study is supported by three multidisciplinary laboratory experiences of the Making Materials[1] research team of Politecnico di Milano, in which end-of-life packaging can be considered no longer a waste to dispose of but a new resource for subsequent production. The collaboration between all the stakeholders in the process is crucial to make this closed cycle work and be efficient.

Introduction

The limited availability of fossil resources, increased pollution caused by traditional plastics and new regulatory restrictions have pushed companies to adopt more sustainable solutions, especially for short-term applications such as packaging. At both global (e.g., Agenda 2030) and European levels (e.g., the European Green Deal and the Circular Economy Action Plan), several strategies and action plans have been adopted to safeguard the planet and promote the use of alternative, environmentally friendly materials for both rigid and flexible packaging (European Commission, 2021; United Nations, 2021). Moreover, in 2019 the European Commission approved the Single Use Plastics (SUP) Directive, which requires the reduction of plastic in single-use applications by encouraging the development of benign and natural alternatives, not chemically modified (European Commission, 2019). Another important step towards the circular economy was taken in November 2022, when the European Commission published new rules for the Circular Economy Action Plan, which follows the ones presented in March 2022 (European Commission, 2022a). The primary focus of this second part is packaging and its related waste.

Unfortunately, the packaging industry is still strongly tied to the linear economy model, in which packaging is designed, produced, consumed and disposed of. Today, the main challenge consists in replacing the traditional linear economic system with a new production and consumption model that promotes the reuse and recycling of materials for as long as possible. In this way, the product's materials are recovered and fed back into the production cycle, reducing waste to a minimum and generating new value. This transition is not simple and immediate; it requires the synergetic effort and collaboration of all actors in the chain: suppliers, manufacturers, recycling processors, distributors, retailers, end consumers and waste service providers (European Parliament, 2015).

In the circular economy context, packaging design and materials choices are crucial in future sustainable innovation. It has been proved that 80% of environmental impacts derive from the design phase (European Commission, 2022b). The designer is, therefore, called upon to intervene in this circular transition phase by adopting a strategic eco-design approach: a sustainable design

[1] Making Materials is a multidisciplinary research group led by Professor Barbara Del Curto engaged in numerous university and corporate projects. The team's main research areas are material selection criteria, development of fibre-reinforced composites, additive manufacturing technologies, nanotechnology, materials and sustainability, smart/active packaging and CMF (colours, materials and finishes) analysis (Making Materials, 2020).

aimed at changing consumer behaviours and habits and ensuring a reduction in waste both at the production and consumption stages (Zeng et al., 2020).

Packaging sector and materials selection

Packaging is now ubiquitous in our daily lives, allowing the containment and protection of goods, and facilitating efficient logistics operations. The global packaging market is expected to grow further in the coming years, reaching over $1.2 trillion in 2028 (Smithers, 2022), resulting in an urgent need for optimising end-of-life technologies. The new rules of the Action Plan for the Circular Economy, cited above, address the problems of the packaging sector and packaging waste in particular (European Commission, 2022d).

Plastics, due to their low cost, lightweight, good durability, mouldability and high barrier properties, are the preferred and most suitable materials for packaging (Filho et al., 2021). European data on plastic recycling recorded in 2020 indicates a positive trend since 2006, but unfortunately, even today, more than 23% of post-consumer waste is sent to landfill (Plastics Europe, 2021). In this case, the durability of plastic becomes a disadvantage: components dispersed in the environment take hundreds or thousands of years to degrade, accumulating in seas, oceans and beaches around the world. This leads marine species to ingest plastic residues that inevitably end up in the human food chain (Filho et al., 2021).

In this regard, the second part of the Circular Economy Action Plan focuses on two main aspects: a proposal for a regulation on packaging and packaging waste (PPWR) and a policy framework on biobased, biodegradable, and compostable plastics (European Commission, 2022c, 2022d). Therefore, European Commission intends to act on two levels: one that, in addition to preventing the production of packaging waste, aims to reinforce the reuse of packaging, increasing the quality of recycling and pushing for the use of secondary raw materials; the other focuses on regulating the implementation of biobased, biodegradable and compostable plastics. From the circular economy point of view, reuse and recharging are the lowest energy-consuming practices and enable the extension of materials and product life (Ellen MacArthur Foundation, 2019). Some cases of companies on the market are already present favouring high-quality materials to guarantee longer life and facilitate reuse, especially in the French and German context: one case is the reusable tableware to reduce waste in restaurants by Elium Studio[2].

Another critical point is recycling: recycled materials for packaging can be of various kinds, from paper to metal and polymer. While for paper or cardboard and the most widely used metals for packaging (e.g., aluminium) there are already well-established recycling chains and standards, for polymers there are some controversies (Ellen MacArthur Foundation, 2016). Firstly, it is necessary to clarify that collected plastic material for recycling is intercepted in two main stages: pre-consumer and post-consumer. In pre-consumer recycling, it is constituted of processing waste: the quality of the resulting product is very high since it has not yet faced external contamination and can thus easily return into the company's cycle. On the other hand, in post-consumer plastic recycling, many more variations and complexities come into play (Genovesi & Pellizzari, 2017); one problem is the variety of plastics on the market. In addition, the contamination with other substances and the regulations governing the use of recyclates often limit their applications. The chemical composition and, consequently, the additives differ considerably depending on the original product, which is mostly unknown (Eriksen et al., 2019). Legislations impose greater control and caution if the recyclate encounters foodstuffs in the application, thus limiting the uses in the food packaging sector, which is the largest source of plastic waste.

The PPWR pushes to increase the recyclate content in plastic packaging as early as 2030. It is foreseen that from 2030, each packaging unit containing plastic parts will have to include set minimum percentages of post-consumer recyclate (European Commission, 2022c):

- 30% in contact-sensitive packaging made with polyethylene terephthalate (PET) as the main component;

[2] Source: https://elium.studio/project/mcdonalds-re-use/

- 10% in contact-sensitive packaging made with plastics other than PET (excluding single-use plastic beverage bottles);
- 30% in single-use plastic beverage bottles;
- 35% in packaging other than those mentioned.

Undoubtedly, the recycled plastics sector still has much to improve to become efficient and help tone down the "war" against plastics, but it could have great potential in terms of the circular economy if rightly optimised.

Another topic mentioned in the Circular Economy Action Plan updates is bioplastics, an alternative to replace traditional fossil-based plastics in the packaging sector (European Commission, 2022c). According to European Bioplastics[3], a plastic material is defined as bioplastic if it is bio-based[4], biodegradable[5] or has both characteristics (European Bioplastics, 2019). The great advantage lies in using renewable resources, thus conserving limited fossil stocks and reducing carbon emissions. In addition, the compostability[6] of some bioplastics offers a new solution for their disposal at the end of the life cycle (European Bioplastics, 2019).

The bioplastics market is constantly growing, as shown by studies and continuous innovations in this field. The global production capacity of bioplastics is set to increase from around 2.23 million tonnes in 2022 to about 6.3 million tonnes in 2027 (European Bioplastics, 2022).

The European Commission's communication aims to shed light on these materials so that their use has a positive environmental impact (European Commission, 2022c, 2022d). The guidelines stipulate that the biomass used in biobased plastics must come from sustainable sources and respect the principle of "cascading use": i.e., prioritising waste and organic by-products as feedstock. Regarding communication aspects, generic definitions such as "bioplastic" and "bio-based" should be avoided by specifying the product's exact share of bio-based plastics. Also, the time and environment of degradation should be indicated, and artifacts with a high risk of dispersion in the environment should not be labelled as biodegradable. Moreover, the use of biodegradable bioplastics must be limited to specific applications for which the environmental benefits and value for the circular economy are proven in order not to incentivise waste dispersion (e.g., mulching cloths). Similarly, compostable plastics should only be used if they have environmental benefits, do not adversely affect compost quality, and where there is a system for collecting and treating organic waste. The products that must be made of such materials are listed in Art. 8 of the PPWR (tea bags, coffee capsules and pods, fruit and vegetable stickers and plastic bags made of ultralight material). Communication should always indicate that the products are certified for industrial composting in line with EU standards and indicate disposal methods using appropriate pictograms (European Commission, 2022c).

A further alternative to fossil-based plastics is biocomposites. They are defined as composite materials consisting of a matrix and a reinforcement of natural fibres (Fazeli et al., 2019). The tasks of the matrix are to hold the fibres together, transfer loads to them, and protect the fibres from environmental degradation and mechanical damage during the product's usage. The fibres used are often

[3] European Bioplastics is a European association founded in Germany in 1993. The organisation is responsible for raising awareness across all relevant stakeholder groups about the benefits of bioplastics. The mission is to reduce the dependency on fossil resources by promoting renewable ones (European Bioplastics, 2022).

[4] Bio-based refers to the fact that the polymer is either entirely or partially obtained from biomass, i.e., from any renewable organic material of biological origin and organic waste (European Bioplastics, 2022).

[5] Biodegradable is the material's ability to convert into substances such as water, carbon dioxide and compost through the chemical process initiated by microorganisms present in the environment (European Bioplastics, 2016).

[6] Compostable defines the ability of the material to decompose biologically under controlled conditions (e.g., a certain temperature, time, etc.). The result of the decomposition process is compost: a biologically stable, inert and odorless organic substance, consisting mainly of humus, active microorganisms and microelements, which can be reused in the agronomic field, for example as a fertilizer (European Bioplastics, 2016).

derived from totally bio-based and renewable sources, such as crop fibres (cotton, flax or hemp), recycled wood, wasted paper, by-products of crop processing, etc. (Sengupta et al., 2017). Regarding sustainability, composites represent a critical materials family since the presence and non-separability of different materials should be a disadvantage. Some biocomposite can be bio-based, biodegradable or compostable, following the rules of the PPWR mentioned above, or some biocomposite material could be presented as recyclable. In this case, the company should establish a circular network or returning system and ad-hoc recycling chain, not compromising existing ones.

The packaging materials application landscape is highly complex and diversified. Without analysing material and its applicative relationship in a real context, it is useless to make sustainability judgements; there are many false myths created around "circular" materials to date. For this reason, this study takes an analytical approach to circular packaging materials, as will be seen in the next section.

Case study mapping

This paper provides an overview of sustainable and circular packaging materials from an in-depth literature search. Making Materials group not only experiments with new materials, as will be shown later, but keeps the trends of new materials under control through systemic mapping (Papile et al., 2022). The case studies presented below were analysed according to the aspects taken into consideration by the research team with the integration of Life Cycle Design (LCD) elements. The LCD methodology (Vezzoli, 2017) considers pre-production (type of resources and raw materials), production (material preparation and processes), distribution (proximity to a local supply chain), use (durability, performance and use/reuse patterns) and end-of-life (disposal and recovery system). All collected data were summarised in Rawgraph[7] flowcharts that offer a clear and intuitive reading of the emerging material solutions.

Fifty circular packaging materials have been mapped, referring to different packaging sectors, contexts, and levels. As shown in Figure 1, the cases belong mainly to food, general product market, cosmetics, disposables, healthcare, luxury and finally, electronics and agricultural packaging sectors. Most of these circular materials for packaging are already industrialised and apply to the consumer market, while only a few cases (n=7) belong to research still in progress or being industrialised.

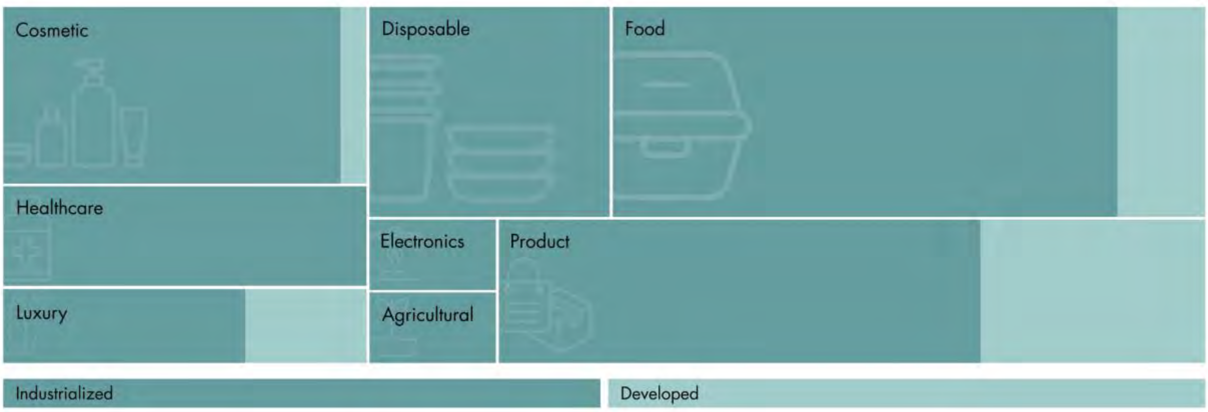

Figure 1. Application fields and maturity level of the analysed case studies.

[7] Source: https://www.rawgraphs.io/

To have a complete overview of the cases studied, they have been mapped by continent and geographical area. As can be noticed from figure 2, the materials mainly originate from Europe, America and finally, Asia; with some countries positioning themselves as major innovators. The year of development of these materials was not easy to identify (only for 31 out of 50 cases), but they mostly cover the time span from 2016 to 2021, as reported in the same picture.

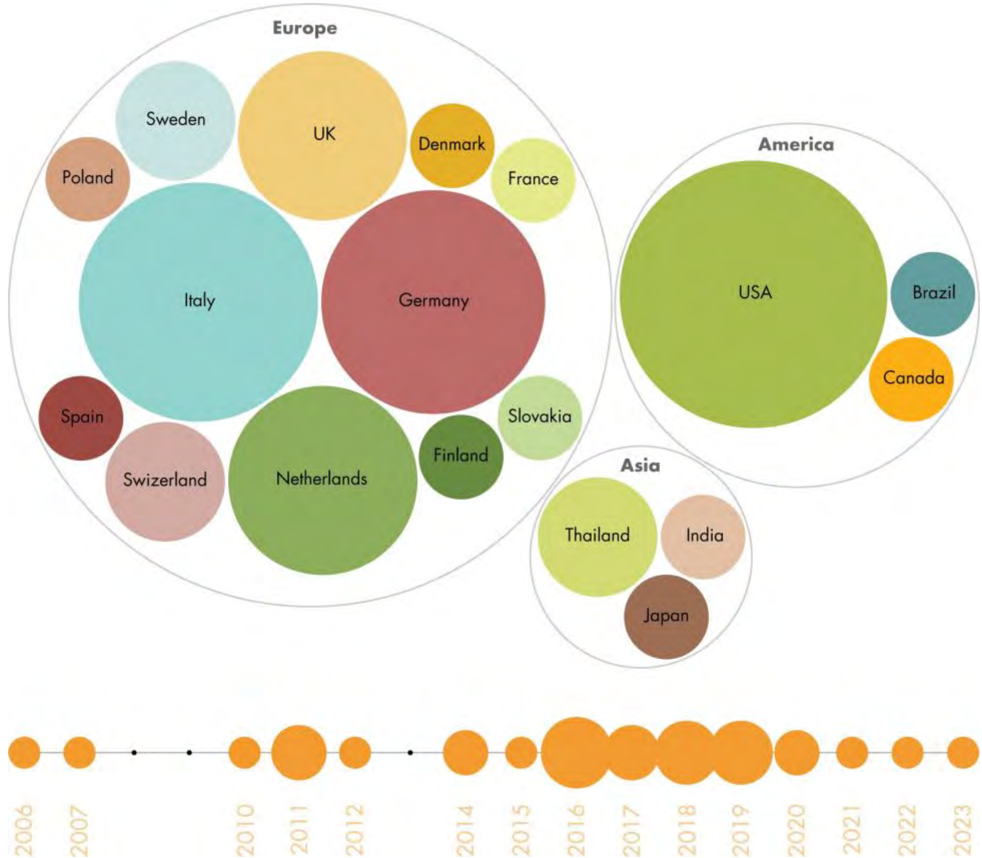

Figure 2. Geographical and temporal distribution of the analysed case studies.

From the extensive mapping of cases, some fields of investigation were extrapolated that were particularly relevant: composition and end-of-life guided the division of cases into emerging lines of research for circular packaging materials. In the visualisation shown in Figure 3, it is possible to find from left to right: the materials and their developers, their composition and clustering into the different research trends tracked. The clustering activity conducted pointed out prominent development trends for incoming years.

In order from the least to the most populated, these are:

- Edible: referring to the food packaging sector, these materials will be consumed together with the packaged food such as dissolvable noodle packaging by designer Holly Grounds[8];
- From recycle: materials entirely from post-industrial or post-consumer collections such as PP Repro by EFS Plastics[9] or from waters such as OWP+ by Pack Tech[10];
- Others: The most ambiguous cases were collected here, with compositions ranging from animal waste (e.g., plumage in the case of Pluumo by

[8] Source: https://www.dezeen.com/2020/07/13/holly-grounds-dissolvable-noodle-packaging-design/

[9] Source: https://www.efs-plastics.ca/products

[10] Source: https://www.oceanwasteplastic.com/

Aeropowder[11]) to recycled textiles as in the case of Nazena by Nazena Sr[12], to mycelio like Mushroom packaging by Ecovative Design LLC[13];

- Cellulose based: mainly composed of cellulose fibre or derivatives, with possible additional waste materials like leather in the case of Remake by Favini [14] or vegetable fibres from tomato plants such as Solidus solution[15];
- Biocomposites: composed of a bioplastic/recycled matrix plus a natural filler like Artichoke fibres in the case of Alveolo da carciofi by IIT[16] or fibres from meadow grass in Agriplast by Biowert[17];
- Bioplastics: Bio-based and/or biodegradable plastics like BIO-PE (Bio-polyethylene) as I'm green PE by Braskem[18] or Terralene HD 4527 by FkuR [19], and materials PHA (polyhydroxyalkanoate) based as for example YOPP PHA by Mango materials[20].

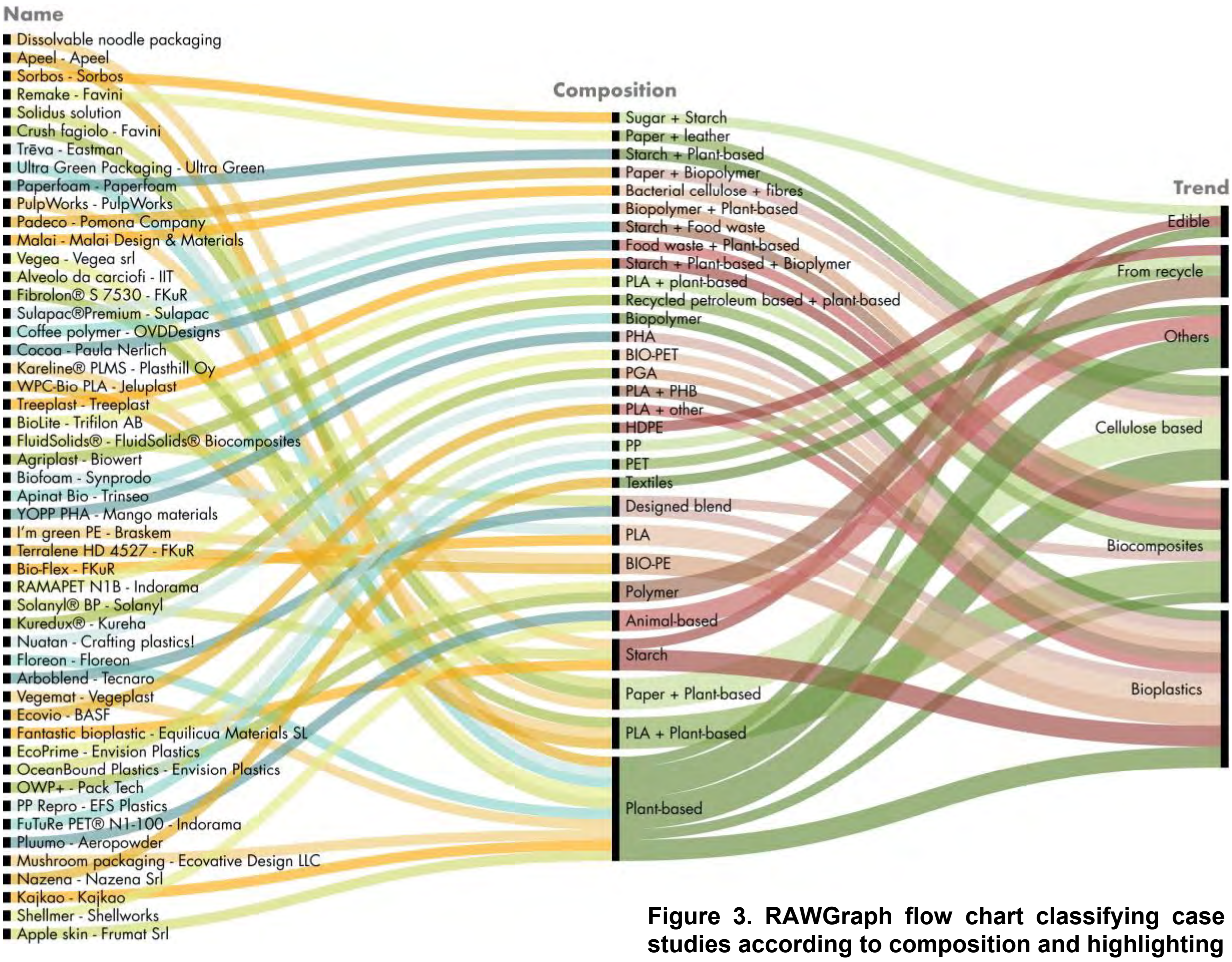

Figure 3. RAWGraph flow chart classifying case studies according to composition and highlighting key development trends.

[11] Source: https://www.pluumo.com/
[12] Source: https://nazena.com/it/
[13] Source: https://mushroompackaging.com/
[14] Source: https://www.favini.com/gs/en/fine-papers/remake/features-applications/
[15] Source: https://www.perishablenews.com/produce/solidus-solutions-produces-solid-board-from-tomato-plants/
[16] Source: https://www.miliardoyida.com/la-nuova-plastica-bio-che-nasce-dal-carciofo/
[17] Source: https://biowert.com/products/agriplast
[18] Source: https://www.braskem.com.br/imgreen/bio-based-en
[19] Source: https://fkur.com/it/bioplastiche/terralene/terralene-hd-4527/
[20] Source: https://www.mangomaterials.com/products-2/#matrixQuadrant1

Notwithstanding the importance of the origin of materials, to ensure their circular life cycle, must be considered the stages of production (energy required for the transformation), transport (affected by geographical proximity), use and disposal (by the entire supply chain and the consumer), and finally the end-of-life, the last step, which can help to close the circle. Most of the materials mapped in this research and summarised in Figure 4 resulted as certified to be compostable, returning to nature by industrial or home composting, technologies in development in most of the studied countries. A large part of materials resulted as mechanically recyclable, although authors are aware that this only occurs in the presence of established supply chains or adequate return systems. While edible, biodegradable and incinerated materials do not assure systemic circularity.

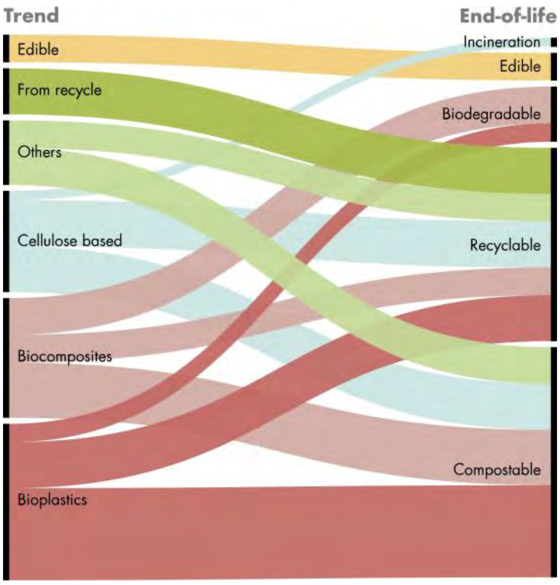

Figure 4. RAWGraph flow chart highlighting the end-of-life of materials belonging to different emerging trends.

Laboratory experiences Making Materials

The Making Materials research group conducted three multidisciplinary laboratory experiments at the laboratories of the Department of Materials Chemistry and Chemical Engineering "Giulio Natta" at the Politecnico di Milano (Milano Bovisa), support the case study analysis carried out and the new emerging trends. Specifically, the experiments were carried out as master's thesis activities and involved the development of new biocomposites for the packaging sector by combining different bio-based, biodegradable and/or compostable matrices with bio-based fillers derived from organic waste, industrial by-products or recycled sources.

The first example is Poly-paper, traceable to the "cellulose-based" trend previously mentioned, a composite material obtained from a fossil-based and biodegradable bioplastic reinforced with up to 60% w/w of recycled cellulose fibres. The result is a material suitable for packaging applications that can be recycled in the paper and cardboard chain and processed like a conventional thermoplastic polymer. The project aimed to integrate the high production versatility of plastic with the high level of recyclability of paper (Santi et al., 2021).

Figure 5. Case study #1: Poly-paper 3D printed packaging.

Another project, positioning between the "cellulose-based" and "biocomposite" trends, involved the development of a composite from 100% bio-based and compostable materials, specifically a polylactic acid (PLA) matrix reinforced with microcrystalline cellulose (MCC). PLA and MCC were selected for their biological nature, wide industrial availability, their biodegradability (MCC) and compostability (PLA). Once the compound was extruded in the different composition ratios, several tests were carried out to fully understand its properties. The mechanical characterisation showed that the new material called PLA:ce has similar properties to ABS and PS, which was useful to identify possible fields of application, including the packaging sector (Marinelli, 2018).

Finally, POMOPLA² is a more recent master's thesis project carried out in collaboration with the Istituto Italiano di Tecnologia (IIT) in Genova. The material is based on polylactic acid (PLA) reinforced with tomato waste, resulting in a new high-performance biocomposite that reuses the by-products from the agri-food industry for both rigid and flexible packaging. The cooperative Finagricola (Battipaglia, Italy) was selected as a possible partner interested in the recovery of its by-products. In addition, a natural, biodegradable plasticiser was added to the matrix to improve the toughness of PLA and expand its market to flexible packaging. Following the principles of circular economy, the idea is to give a second life to tomato production waste through the development of POMOPLA², a promising substitute for the current packaging in PP, PE and PET used by Finagricola for fresh tomatoes (Rotondo, 2022).

Figure 6. Case study #3: POMOPLA² 3D printed packaging prototype.

In an ideal system (see Figure 7) if POMOPLA² passes the ongoing tests of biodegradability and compostability, the packaging after use can be composted together with the remaining tomato residues (branches, peels, etc.). In composting plants at elevated temperatures and humidity, the organic waste is processed to obtain compost, a natural and ecological fertiliser that can at least partially replace chemical fertilisers for a new agricultural production. Starting from nature, the extent is to return to it through a responsible and endless cycle (Rotondo, 2022).

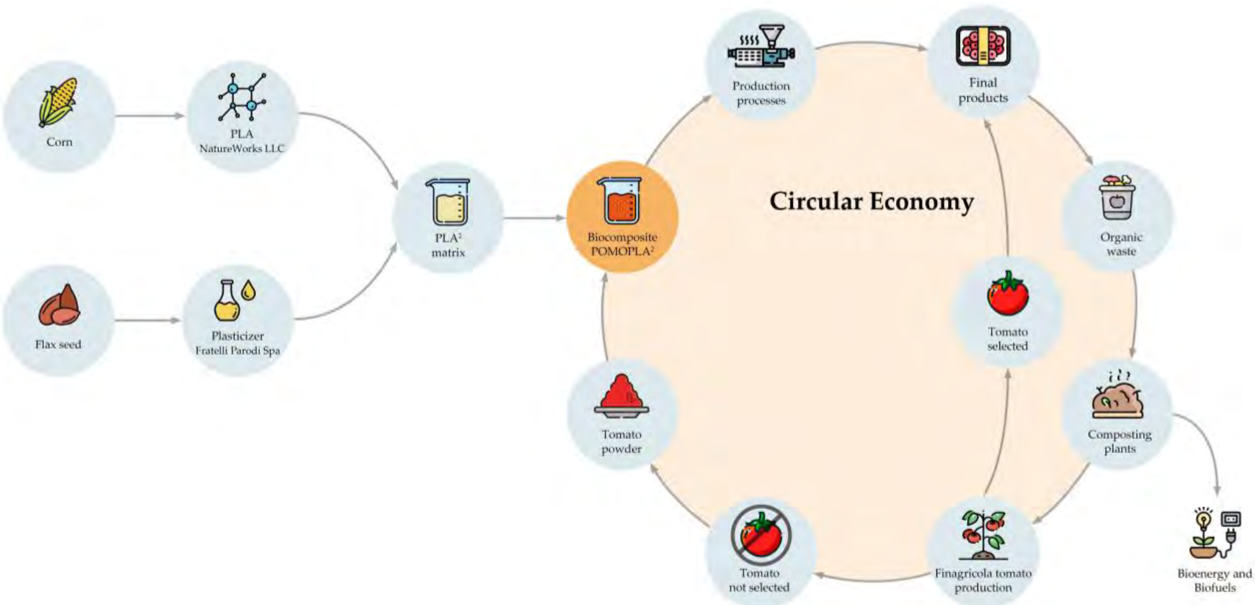

Figure 7. Case study #3: POMOPLA² ideal life cycle.

Conclusions

Circular materials are gaining more and more interest, as demonstrated by the analysis and exploration of the case studies illustrated above. However, it is important to emphasise that not all the solutions presented have the same level of circularity and sustainability. Before selecting the right material, it is important to identify the requirements for the specific end application and to understand the entire life cycle of the product and, thus, of the related material. Adopting eco-design strategies during the packaging development phase makes it possible to achieve a good level of eco-efficiency of the product by considering all related environmental, economic and social aspects.

The research is an ongoing activity, continuously expanding the circular materials database to stay updated with new emerging solutions in the packaging sector and to provide a comprehensive and detailed overview that can be consulted and easily used by companies, start-ups and universities. The library will also show current trends and guidelines for developing new sustainable materials following the circular economy principles. Cycles in which a close synergy between all players in the system is necessary, not forgetting the consumer, who must be informed and educated on the correct use and disposal of materials through appropriate labelling and awareness campaigns. By adopting a collaborative and cooperative attitude, it would be possible to develop more environmentally friendly packaging solutions and help preserve the planet's resources, giving new life to scraps and generating zero waste.

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