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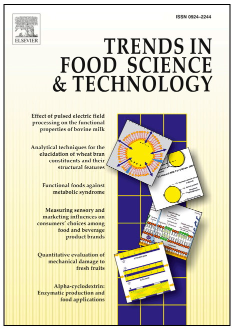

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Perspectives on sustainable food packaging:
– is bio-based plastics a solution?

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Abstract

Background: The demand for more sustainable packaging materials is increasing. However, the multidisciplinary and complexity of this topic often lead to misconceptions among food packaging designers and producers, which challenge the creation of more sustainable food packaging systems.

Scope and Approach: This manuscript presents in a holistic perspective the most relevant parameters that need to be considered for sustainability in food packaging and aims to increase the awareness of food and packaging producers to create effective sustainable packaging materials for foods.

Key Findings and Conclusions: The use of bio-based plastic packaging materials contribute to create more sustainable food packaging materials, comparatively to conventional plastic packaging materials, when looking at climate impact responses. Although bio-based plastic packaging materials have reduced climate impact, there are other environmental impacts (e.g. eutrophication, use of water and pesticides, effects on biodiversity) that are less favorable for using bio-based materials and should also be considered. Recycling of the packaging significantly contributes to reduce its environmental and climate impacts. The sum of the climate and environmental impacts of the packaging should be seen together with the food it protects. The combined system should be assessed in its entire lifecycle and optimized through the design, production and end life of the packaging material to improve its sustainability.

Keywords: Food Packaging, Plastics, Bio-based materials, Sustainability, Life Cycle Assessment, Plastic recycling

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1. Introduction

Packaging materials are part of our daily life. When it concerns foodstuffs, they play a pivotal role to ensure that food products are preserved with a desired lifetime and subsequent optimization of space during handling, shipping, and storage for a minimum of wastage (Russell, 2014)(de Léis et al., 2017).

For many years petroleum-based polymer materials have been used as plastics packaging, such as polypropylene (PP), polyester (PET), polyethylene (PE) and polystyrene (PS) (Salwa et al., 2019). The production of plastic packaging has increased twentyfold since 1964 and represents the largest application of polymers with 26 % of the total volume. Due to its many good characteristics (e.g. lightweight and good barrier properties) plastics have increasingly replaced other packaging materials, and the production is expected to continue growing to the double volume within the next 20 years (MacArthur et al., 2016).

Although plastic packaging have been performing successfully in terms of their functionality, the production of petroleum-based plastics releases greenhouse gases (in particular CO_2), and in their disposal, due to the lack of collection or proper handling, plastics tend to end up in landfills or become trash on land and water streams and ultimately contaminate the oceans (Geyer et al., 2017; Salwa et al., 2019). Industry is struggling to find a more environmentally friendly way of producing and using plastic. The overall question is how can plastic become (more) sustainable?

In this context, food-packaging producers and food industries have been working towards the use of abundant, low cost, renewable, and biodegradable alternatives to the traditional, nonrenewable petroleum-based resources (Chi et al., 2020), such as the bio-based plastics (Kawashima et al., 2019). They offer the possibility to reduce the use of petroleum resources with potential subsequent reduction of the CO_2 emissions (Salwa et al., 2019).

It is estimated that the eco-friendly food packaging market will increase, with a shift in consumer preference towards materials that are recyclable and “eco-friendly”. However, there is still great uncertainty about the potential and possible advantages of bio-based plastics compared to conventional plastics and several misconceptions exist.

To reduce the generation of plastic waste the EU Commission set an ambitious goal of 55 % of plastic packaging recirculation in 2025 and that in 2030 all plastics are recyclable (or reusable), following a Circular Economy approach. This puts a pressure on increased recycling and reuse of plastic packaging also for food, as this represents the largest fraction of all plastic packaging in EU ("Plastics - the Facts 2014/2015: An Analysis of European Plastics Production, Demand and Waste Data," 2015).

Evaluating the sustainability of food packaging requires a wider perspective comprising several aspects (Russell, 2014). This should include the use of materials that: create no greenhouse gas emissions, have the potential to be recycled or reused, generate zero landfill waste, reduce water use, are made using renewable energy, do not produce air pollution and do not harm human health, among many other considerations.

Although progress has been made towards the creation of alternative packaging systems, there is not yet a perfect a solution that can meet the many criteria for sustainability and ultimately fulfill the functionality of the food packaging: to preserve and deliver the packed foods in good condition (Russell, 2014). This manuscript will identify and discuss the most relevant indicators in a holistic perspective to create more sustainable food packaging systems.

2. Materials used in food packaging

Plastic packaging (rigid and flexible) constitutes the main type of food packaging(Asgher et al., 2020) followed by paper and board (Muller et al., 2017)(*Your 2020 Complete Guide for Food Packaging*, 2020). Figure 1 displays common plastic materials used in packaging and Table 1 shows examples where those materials can be applied.

2.1. Petroleum based plastic materials

Common plastics used in food packaging include synthetic polymers such as polyethylene terephthalate (PET), polyvinyl chloride (PVC), polystyrene (PS), polypropylene (PP), and polyethylene (PE) (Roohi et al., 2018)(Ahmadzadeh & Khaneghah, 2020). Those plastics are mostly obtained from feedstocks derived from petroleum and natural gas (Ahmadzadeh & Khaneghah, 2020). Overall, petroleum based materials are known for their easy processability, low cost, good mechanical and barrier properties**,** lightness, transparency, tensile strength but also lack of degradability in the nature (Roohi et al., 2018)(Ahmadzadeh & Khaneghah, 2020). Their production moreover, causes emissions of greenhouse gas (CO_2) which contributes to imbalance the climate of the planet with consequent environmental damages (Ahmadzadeh & Khaneghah, 2020).

2.2. Bio-based plastic materials

Bio-based plastics include: 1) natural biopolymers and 2) polymers synthesized/polymerized from natural feedstock monomers (e.g. polylactic acid, bio-PET, bio-PE). The natural biopolymers are already existing polymers in the nature, and can be defined as a polymeric compounds occurring in living organisms. They can be extracted from: i) plants (e.g. starch, cellulose, zein), ii) animals (e.g. milk proteins), or microorganisms (e.g. xanthan and other polysaccharide gums). Natural biopolymers in food packaging are used to produce both plastic films and paper. The fact that a polymer is bio-based does not mean that it is biodegradable (able to degrade into monomers, water, CO_2 and/or methane (CH_4) caused by microorganisms biological activity (Hann et al., 2019; Rudnik, 2019)) or compostable (degradable under specific conditions) (Rudnik, 2019).

Natural biopolymers are often biodegradable in the environment whereas only a few bio-based plastics made of bio-based monomers are actually biodegradable or compostable (e.g. PHAs, PLA, polyester amides) (Halonen et al., 2020). Bio-based substitutes for petroleum based plastics such as bio-polyethylene, bio-polyamide and bio-polyethylene terephthalate are no more biodegradable than their petroleum-based counterparts (Halonen et al., 2020). Figure 1 gives an overview of the characterization of plastics according to feedstock and biodegradability. As seen Bio-PET (26 %), produced with bio-based ethylene glycol monomers, is the most prevalent bio-based non-biodegradable plastic on the market and starch blends (18%) the most prevalent biodegradable biopolymers.

The market for bio-based plastics started in the early 1990s (Kawashima et al., 2019)(Shogren et al., 2019), due to the early awareness of the need of creating more sustainable societies and circular economies considering resource conversion, efficient after-use utilization, and environmental protection (Kawashima et al., 2019). Currently, the production of bio-based plastics accounts for only about 1 percent of the total amount of plastics produced annually (European Bioplastics, 2019). The production of bio-based plastics is still low, however it is expected to gradually increase from 2.11 million tons in 2019 up to 2.43 million tons in 2024 (Halonen et al., 2020).

3. Requirement for food packaging materials

3.1. Packaging functionality

Packaging should preserve the food quality to improve its shelf life. Packaging mechanical, strength, thermal and barrier properties (e.g. to light, moisture, water vapor, and oxygen/ other gases), should match the needs of the given food. Thus, the food packaging system must be able to obstruct either moisture gain or loss (depending on the type of food), control the permeation of water vapor, oxygen, carbon dioxide and other volatile compounds and prevent all types of contamination (Salwa et al., 2019).

3.2. Chemical food safety of packaging

Packaging is used to protect food from contamination, degradation and spoilage and thereby increasing its shelf life, therefore it should not contribute to the chemical contamination of the food from itself. EU regulation 10/2011 (EU Commission, 2011) holds a list of authorized starting substances allowed in the production of food contact plastics. When plastic packaging come into contact with food, chemical substances in the packaging can potentially migrate into the food. Migration from plastic into food is a process governed by diffusion (in the material) and sorption (from the packaging to food). According to the regulation, EU 10/2011 (EU Commission, 2011), migration of specific substances must not exceed the specific migration limits (SML) given in the regulation. It is the responsibility of industry to ensure that the material complies with the regulation and documents this in the whole production chain.

Also, non-intentionally added substances (NIAS) (Geueke, 2018) such as degradation and reaction products of the starting substances, impurities added from the materials or processes may occur in the plastic material. These NIAS are not authorized and it is the obligation of the food contact material manufacturer to ensure the safety in accordance with Article 3 of the EU Framework Regulation (EC) No 1935/2004 (EU Commission, 2004) for materials and articles in contact with food.

Bio-based plastics may also release NIAS. These substances may potentially include pesticides and natural toxins in the plants used as biomass feedstock. According to a recent report on bio-based food contact materials, no data was found regarding migration of pesticides or natural toxins from bio-based plastics into food (Bonwick et al., 2019). If nanoparticles are used in the packaging material, as for instance with the bio-based materials to improve barrier properties, the potential risk needs to be assessed on a case-by-case basis as stated by the European Food Safety Authority (EFSA) and given in the EU Regulation 10/2011 (EU Commission, 2011).

3.3. Environmental impact of the packaging

The environmental impact of the packaging arises from the sourcing of the feedstock, the production of polymers and packaging, and end of life treatment of the packaging. In all these stages, emissions to the environment may contribute to negative environmental impacts including climate change, air pollution, acidification, water pollution and eutrophication. The impacts from the packaging life cycle shall be as low as possible without compromising the first two properties mentioned in section 3.1 and 3.2. Food waste is an increasing concern as around one third of all (globally) food intended for human consumption is lost or wasted from industry and households (Gustavsson, Jenny; Cederberg, Christel; Sonesson, 2011). The food manufacturers generate a significant amount of organic waste but succeed to recover most of it (almost 90%) into e.g. animal feed or compost. According to Verghese *et al*, 2013 (Verghese K., Lewis H., 2013) the largest opportunities to further reduce food waste lie within other parts of the supply chain covering in particular the distribution and retail system, food services and households (Verghese K., Lewis H., 2013). In this context, packaging decisions and designs can directly influence the amount of food waste (Svanes E., Vold M., Møller H., Pettersen M. K., 2010). Evaluation of the packaging performance addresses microbiological, sensory, physical and chemical properties of the given food. Studies on cucumbers have shown that a plastic wrap prolongs shelf life from 3 up to 14 days because it prevents evaporation and for broccoli, active packaging film was found to increase the shelf life by up to 20 days (Lindh H., 2016). Food packaging that fails to protect its content, thereby causing food and packaging waste, is a waste of invested resources and an unnecessary environmental burden.

The product and packaging volume ratio has a positive environmental influence through increased efficiency during storage and transport. Also the packaging facilities such as easiness to open, pour and re-seal, can influence how much of the packaged food will be consumed and not wasted in households (Lindh H., 2016).

4. Sustainability of food packaging

Sustainability can be defined as meeting the needs of the present generations without compromising the ability of future generations to meet their needs (*World Commission on Environment and Development, 1987*, 1987). The concept of sustainability comprises three dimensions: economic, environmental, and social. This paper focuses on the environmental dimension.

Production of food uses energy, water, fertilizers and often pesticides, and it causes emissions of pollutants, including greenhouse gases, in amounts that are much higher than the production of the packaging material. It is estimated that 29 % of global greenhouse gas emission is from production of food (Vermeulen et al., 2012).Therefore, to evaluate the environmental impact and sustainability of a food packaging both the packaging and the food need to be considered in a product-packaging combination (Svanes E., Vold M., Møller H., Pettersen M. K., 2010)(Pauer et al., 2019).

For rye bread and ham, the amount of greenhouse gases emitted from the production of different packages (PP, PE and laminates of plastic or paper/plastic) was estimated to be 1-3 %

of the packed food, whereas for soy based yoghurt (soyogurt) the polypropylene package had about 10% of the total greenhouse gas emission of the package-product system (Silvenius et al., 2011). The production of meat products and dairy products have higher environmental impacts compared to grain, vegetables and fruit (Clune et al., 2017)(Poore & Nemecek, 2018). Life cycle assessment (LCA) can be used to evaluate the environmental impact of a packaging (including the product-package combination) in its entire life cycle. The principle is to quantify the materials and energy used, the waste and emissions produced and to assess the environmental impacts in the different stages of the entire life cycle of the product (Hann S., Scholes R., 2020). The principle and general methodological framework of performing LCA is given by the ISO 14040 series(*ISO 14040:2006 - Environmental Management — Life Cycle Assessment — Principles and Framework — Amendment 1*, 2020). Different internationally accepted models and guidelines are available to perform LCA, including the European Commission's guideline: The ILCD Handbook (Pennington et al., 2010).

A full life cycle of the product value chain of a food-package includes the following 4 main stages:

1. Source of material and production of the packaging and the food product
2. Packaging of the food product
3. Distribution (transportation and storage) of the food-package product: protection of food by the packaging material (functional properties of the packaging in use in relation to shelf life of the food and chemical food safety of the packaging)
4. End of packaging life

The output of an LCA should make it possible to: i) identify the most relevant impacts (e.g. climate change, acidification etc.) of the product; ii) identify the processes that generate the highest environmental impact (e.g. manufacturing of the packaging material, food packaging processes or packaging transport); iii) propose guidance for improvement of the system/product (Vignali & Vitale, 2017).

LCA of the food-package system shall include the indirect environmental impact of the packaging caused by its influence on the food product's life cycle and in particular its influence on the generation of food waste (Molina-Besch et al., 2019). If the focus is only on the direct environmental impact of the packaging itself, it may lead to recommendations for packaging with increased environmental impact of the food-package combination. A low impact packaging may have poorer properties in protecting the food and therefore lead to a larger loss of the packaged food.

4.1. Production of plastic packaging

LCA studies of PLA bio-based plastic show advantages in climate protection and conservation of fossil resources in comparison to petroleum based plastics. In a meta-analysis of bio-based materials, LCA of 44 different cases were performed (Weiss et al., 2012). The evaluation concluded that bio-based materials generally exert lower environmental impacts than conventional materials in the category of climate change (neglecting greenhouse gas emissions from changes in land use due to the production of biomass).

The choice of feedstock for production of bio-based plastic is however important, as it matters greatly whether the feedstock is considered to be a primary crop, or a by-product or waste from another process (Hann S., Scholes R., 2020) (Weiss et al., 2012) If feedstock is produced from first generation biomass (defined as biomass that is generally edible) such as maize or starch, the growing of this biomass will compete with the production of crops for human consumption and may cause a need of more cultivated land (see Figure 2). If the bio-based plastic is made from waste feedstocks (second generation feedstock) it is considered burden free and will perform better in an LCA.

Climate change from greenhouse gases is not the only relevant environmental impact from the production of the plastic. The need for bio-based feedstock materials is heavily associated with other environmental effects from the biomass production. The most relevant environmental impact categories, that are internationally accepted for evaluation of environmental impact of food packaging include natural resource depletion, acidification, photochemical ozone creation, eutrophication, human toxicity and aquatic toxicity (Hann et al., 2019)(Vignali & Vitale, 2017)(Weiss et al., 2012)(Life Cycle Assessments of Biodegradable, Commercial Biopolymers - A Critical Review, 2013)(Maga et al., 2019)(Ögmundarson et al., 2020).

The evaluation by Weiss *et al*. (Weiss et al., 2012) showed that bio-based materials may exert higher environmental impacts than their petroleum based counterparts in the categories of eutrophication and stratospheric ozone depletion. In addition, most bio-based materials have environmental impacts caused by the application of pesticides during the cultivation of biomass. With regard to acidification and photochemical ozone formation the studies found high variability and were inconclusive.

A comparison of bio-based PE to petroleum based PE showed that the impact categories climate change, summer smog and consumption of fossil resources were lower for bio-based PE compared to petroleum based PE. However the opposite situation was found for acidification potential, terrestrial and aquatic eutrophication, human toxicity, water consumption, total primary energy demand and land use, where environmental impact of bio-based PE was higher than conventional PE (Hann S., Scholes R., 2020).

4.2. End of life of packaging

4.2.1 Degradation and composting of plastics

Composting of plastic is often considered as an environmentally attractive and sustainable way to reduce the municipal waste problem. The degradation of petroleum based plastic materials is about 1% over 100 years and thus negligible in landfills. This also applies for the bio-based counterparts bio-PET, bio-PE and bio-PP, and as mentioned previously, not all bio-based plastics are biodegradable. The biodegradable plastics constitute 43 % of the current use of bio-based polymers with starch blend polymers and PLA as the most common (Hann et al., 2019). The aerobic degradation into CO_2 and water requires oxygen while the anaerobic degradation takes place in the absence of oxygen and produces methane (CH_4) rather than CO_2. Methane is a much stronger greenhouse gas than CO_2 with 28 times higher contribution to global warming ("Climate Change 2014: Synthesis Report IPCC," 2015). The degradation of biodegradable plastics can result in significant emission of greenhouse gases (CO_2 and CH_4) into the environment when disposed in landfills.

Many degradable plastics are not biodegradable in the natural environment but have temperature and time requirements that require controlled industrial composting to ensure effective degradation (Kijchavengkul & Auras, 2008) (Álvarez-Chávez et al., 2012). It is therefore important to specify under which conditions and within which timeframe a given kind of plastic is able to degrade.

4.2.2. Recycling of plastic

Several studies conclude that recycling is a key for improving environmental sustainability due to the generally lower life cycle impacts of recycling processes, compared with production of the virgin materials that are replaced by the recyclates (EU Commission, 2018) (Watkins et al., 2019). However, only 14 % of all plastic is collected and recycled, and the plastics that are recycled are mostly downcycled into lower value applications from which they cannot enter another round of recycling (MacArthur et al., 2016).

According to the EU Commission, the potential for recycling plastic waste remains largely unexploited in EU. Reuse and recycling of end-of-life plastics is very low, particularly in comparison with other materials such as paper, glass or metals (EU Commission, 2018). Many factors lead to this situation, including: dissipative material losses during the use stage of a product; loss of material through improper collection, material quality becoming degraded during collection and processing (downcycling), build-up of stocks, product designs that impede recycling, lack of suitable waste collecting and recycling infrastructure; contamination with hazardous substances and economic factors resulting, for example, from the need for decontamination and price competition with virgin materials. Additionally, transportation may significantly contribute to a number of environmental impacts in the recycling scenario (Madival et al., 2009) depending on the distance of the transportation of the recycled waste.

Mechanical recycling, which involves sorting, grinding, washing and extrusion of material is the most used packaging plastic recycling method. The mechanical recycling potential depends on the polymer composition, its mechanical properties and its chemical safety (Danish Plastics Federation, 2019)

During the various steps of the recycling process, e.g. high temperature treatments, the polymeric chain may break down to smaller molecules and additives or sorbed compounds may react and be converted into new compounds which can affect the mechanical properties and/or the chemical safety (EFSA, 2011) of the plastic. A particular challenge in recycling packaging materials occurs with multi-layer food packaging systems, which contains different polymers that are impossible to separate and recycle into separate high quality polymers (Matthews et al., 2021). Chemical recycling technologies degrading the plastic into chemical feedstock or monomers are suggested as potential alternative recycling methods for materials that are not suitable for mechanical recycling (Matthews et al., 2021). The environmental impact of different end of life options should be evaluated by LCA and economic analysis to decide for the most sustainable and cost effective solutions. With the introduction of bio-based packaging materials with novel polymers, design for improved recyclability is still essential to support the transition to a circular economy and the sustainability of bio-based plastics (Hatti-Kaul et al., 2020). Compostable plastics as e.g. PLA may technically be recyclable but at present, the waste infrastructure cannot handle this (European Bioplastics, 2019). PLA is difficult to distinguish from PET in the recycling systems and will contaminate and degrade the quality of the PET recyclates if not effectively sorted out.

Human health risks can arise from the migration of contaminants present in the recycled plastics into the packaged food. The following potential contaminants of recycled plastics are considered by the European Food Safety Authority (EFSA, 2011): non-authorized monomers and additives; contaminants from possible misuse of the packaging; contaminants from non-food consumer products (e.g. cosmetic, personal hygiene products, household cleaning) or from the packed food; chemicals from other materials of the packaging (e.g. printing inks, glues, sleeves or labels) resulting from incomplete sorting and separation; chemicals added in the recycling process, and degradation products and/or reaction products of the plastic. Consequently, the recycling process must ensure contamination levels that are safe for human health and in accordance with the EU regulations 1935/2004 (EU Commission, 2004) and 282/2008 (EU Commission, 2008). The recycling processes are authorized by the Commission based on safety assessments performed by EFSA on a case-by-case basis (EFSA, 2021) in accordance with EFSA scientific opinions on mechanical recycling (EFSA, 2008)(EFSA, 2011)(Barthélémy et al., 2014). Some of the given criteria (EFSA, 2011) are specific to PET and, therefore, cannot be applied directly to other plastics e.g. PE or PP (EFSA, 2015). Due to a high diffusivity of PE and PP, contaminants are more effectively absorbed into these polymers (compared to PET) with high risk of chemical migration into food if not sufficient decontamination of the input material or recycling in a closed and controlled loop. A guideline with specific criteria for recycling of PP and PE (mechanically or by alternative technologies) has not yet been published by EFSA. However, a few processes of mechanical recycling of PP and PE have been assessed by EFSA on a case-by-case basis also concluding that more data will be needed for a better safety assessment of these kinds of plastic (2010, 2015, 2018).

5. Discussion and perspectives about sustainable food packaging

Sustainability is becoming a main priority in the food industry, and food packaging is one of the areas where food industries should invest. Therefore, there is the demand to produce and use materials that are: i) safe and without risks to human health or the environment during the packaging life cycle; ii) matching the market needs in terms of performance and cost; iii) preferentially produced, transported and recycled (or in special cases composted) using renewable types of energy and iv) produced using clean and energy-efficient production technologies.

Petroleum based plastic materials, are still the main type of materials used in food packaging, as generally they offer excellent barrier and mechanical properties for the different types of food. They have been optimized to specific foods using technologies such as multi-layer materials and modified atmospheres (Mangaraj et al., 2009). Yet, the fossil resources may be scarce in the future, although petroleum used for plastic manufacturing only covers around 4 % of total petroleum used globally (Hopewell et al., 2009)(British Plastic Federation, 2019). EU demands a reduction in the greenhouse gas emissions, and packaging must be also targeted by increased recycling in a circular economy (EU Commission, 2018). It is estimated that plastics production and the incineration of plastic waste globally give rise to approximately 400 million tonnes of CO_2 a year (EU Commission, 2018). Increased recycling would also potentially reduce the amount of plastic waste in the environment.

This has lead to an increased industry interest in bio-based plastics as a potential solution to make food packaging more sustainable. Bio-based materials produced from renewable resources reduce the use of fossil resources and the greenhouse gas emissions are in general lower than petroleum based plastic.

Bio-based plastics include bio-PET, bio-PP and bio-PE that have been produced from biomass feedstock with identical chemistry and functionality to petroleum-based plastics, and plastics produced from natural feedstocks such as PLA or PHA. Those aim to replace some of the petroleum based plastics in terms of their functionality for specific food packaging applications.

Natural biopolymers such as polysacharides and proteins are often abundant, low cost and biodegradable (Yang et al., 2015). Polysacharides such as starch (particularly thermosplastic starch) and cellulose have been used in combination with other materials (composite materials) to produce food packaging systems (Shogren et al., 2019). Other polysacharides such as chitosans (Katiyar et al., 2019)(Cazón & Vázquez, 2019)(Katiyar et al., 2019), pectins and other gums (Kumar et al., 2017) have also been investigated as potential alternative packaging materials. However, most of the polysaccharides are hydrophilic which means they may absorb moisture and water, resulting in rapid dissolution under aqueous environments and poor barrier properties (Luís et al., 2019)(Kumar et al., 2017). Some proteins can more easily resist the water solubility problem and offer better water and gas barrier and mechanical properties (Luís et al., 2019).

In many cases, the barrier properties towards gas and water of monolayer bio-based plastics are insufficient to preserve and effectively protect the foods. However, for some types of foods, the permeability of bio-based materials may increase the shelf-life of food compared to conventional plastic packaging. This may apply for fruit, vegetables and bread because of increased breathability of some bio-based polymers. Furthermore, when needed, some mechanical and barrier properties of the natural biopolymers can be improved by coatings, nanotechnological processes, blending of materials, laminates of different plastic types and chemical and physical modifications. Yet, these are not competitive solutions to replace petroleum based food packaging materials in the markets. Another concern for natural biopolymers is to ensure that materials produced from different batches have the same properties to ensure reproducibility and suitable functionality of the final packaging material. Quality standards and improved engineering to produce reproducible material compositions is essential.

Moreover improving the production efficiency of bio-based feedstock can become a key parameter to potentially make bio-based materials more sustainable. The ability of bio-based materials to reduce climate impacts compared to petroleum based plastics depends on several factors and in particular on the source of feedstock. Moreover, also several other potential environmental impacts need to be considered.

When bio-based materials are produced from second generation feedstock (agricultural waste that does not compete with food production) the climate and environmental impacts are negligible or low. However, when the biomass is produced from first generation feedstock (crops) a conflict of interest in land use between food and bio-based plastics (and also biofuels) is foreseeable. The increased demand for biomass production causes indirect land use change that can lead to deforestation and harvesting of new land which will lead significantly to increased CO_2 emission from degradation of organic matter in the soil humus(Life Cycle Assessments of Biodegradable, Commercial Biopolymers - A Critical Review, 2013). It is the overriding trend that for bio-based plastics, the feedstock production causes negative environmental impacts more than any other life cycle stage of these materials (Hann et al., 2019). The overriding trends show advantages to bio-based plastics over petroleum based plastics for climate impact and consumption of fossil resources but also disadvantages primarily from feedstock production causing environmental impacts such as increased acidification and eutrophication (Hann et al., 2019).

Regarding packaging end-of-life, several studies have concluded that recycling of the packaging significantly contributes to reduce its environmental and climate impacts. It is also concluded that mechanical recycling has the lowest impact among current recycling techniques. Among the conventional petroleum based plastics so far only PET is approved by the EFSA within given conditions to be used as chemically safe mechanically recycled material in contact with food (EFSA), 2011). To make mechanical recycling possible it applies to all kinds of packagings (petroleum or biobased) that the design should favor monoplastic materials or multimaterials that are easily disassembled. This can be in conflict with requested high barrier properties of bio-based materials often obtained by blending of materials or lamination of different plastic types. More research is needed in terms of material properties and designs of bio-based packagings that both efficiently preserve the food and improve recyclability of the safe materials at their end of life.

Biodegradable or compostable plastic is often considered as being a solution to the climate and environmental impact of plastic packaging. However, when biodegradable materials of all kinds are disposed in a landfill (where degradation is often anaerobic) they will contribute to greenhouse gas emission, including methane with 28 times higher contribution to global warming than CO_2 (“Climate Change 2014: Synthesis Report IPCC,” 2015). When this is taken into account in the total life cycle assessment of biodegradable plastic packaging, this significantly increases the climate change environmental impact of biodegradable plastics.

Compostable materials that are not biodegradable in the natural environment or landfilling have to be processed in an industrial composting plant to degrade by the end-of-life. Studies have shown that when industrial composting is compared to other end-of-life scenarios (as landfill, mechanical recycling, use as fuel in thermal processes, anaerobic digestion and municipal incineration) the industrial composting shows the highest impacts for most of the environmental impact categories (Rossi et al., 2015). In addition, it is found that composting of materials like e.g. PLA and TPS (thermoplastic starch), with very low content of the macro nutrients N-P-K does not make the compost useful as fertilizer (Rossi et al., 2015).

When end-of-life is taken into consideration in LCA of bio-based materials, biodegradation or composting of the materials does therefore not add to a more sustainable performance. On the contrary if recyclability of bio-based materials becomes possible (reducing the need for growing of biomass and production of new plastic) it would have major positive benefits on life cycle impacts of these materials. However, in such cases where packaging are heavily contaminated with food (and cleaning would need much water) composting of the packaging (as e.g. PLA or starch) together with the wasted food could be preferable (Rossi et al., 2015).

The basis for a recyclable and circular packaging starts with the design of the packaging and selection of appropriate materials. Better design can make products last longer and/or make it easier to disassemble and recycle them at the end of their life.

6. Concluding remarks

New innovative plastic packaging materials (bio-based as well as petroleum based) for food should prioritize and optimize the following parameters in their design as the main indicators for more sustainable packaging: i) the materials should have the most optimal barriers to improve shelf life of the food and reduce food loss; ii) the packaging should be designed for (mechanical) recycling, iii) bio-based materials should be efficiently produced from second generation feed stock. Preference goes to the use of mono plastic materials for which functional properties and chemical safety are maintained in the recycling of the packaging material. Avoiding the use of chemicals of concern reduces both environmental and human health impacts as well as waste management costs.

Bio-based plastic packaging materials are found to have reduced climate impact compared to conventional packaging materials. However, other environmental impacts of bio-based materials should also be considered. The sum of climate and environmental impacts of the packaging/food systems should be assessed in its entire lifecycle and minimized trough the selected design.

The design for more sustainable food packaging is a complex task, as many different parameters need to be considered. LCA tools are available and should be used to quantify and compare environmental impacts from different packaging designs considering the integrated packaging/food system. By the help of LCA it should be possible from an informed and holistic foundation to make decisions on how to improve the sustainability of food packaging.

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Figures and captions

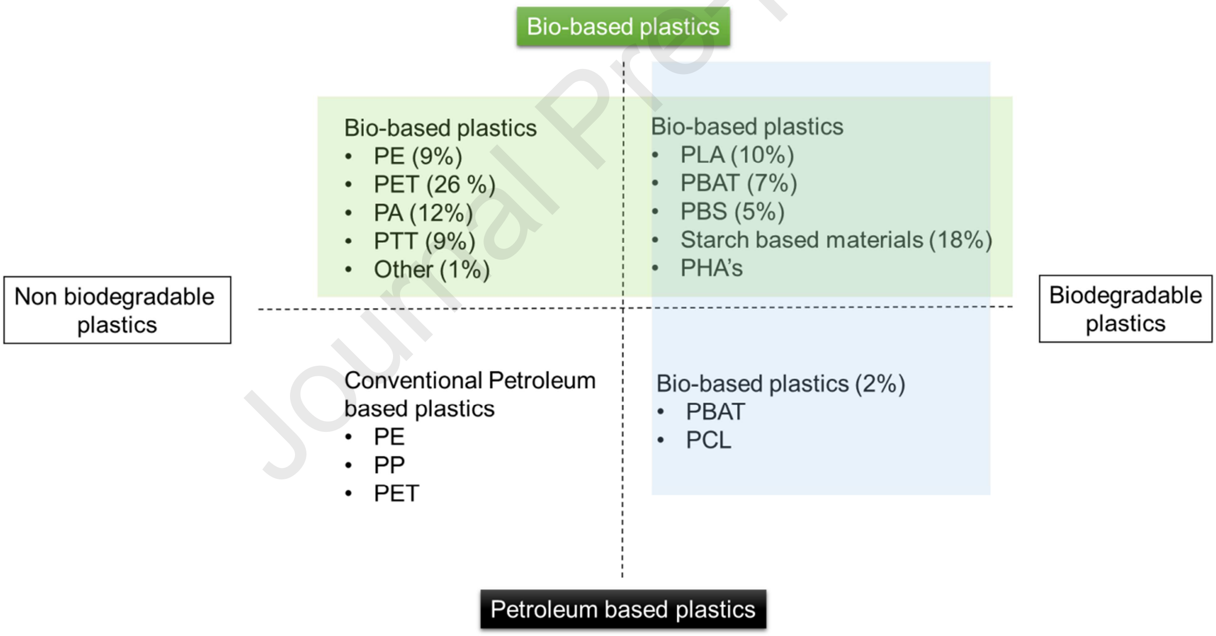

Figure 1. Characterization of common plastic materials used in packaging according to their feedstock origin and biodegradability properties, market shares in brackets for bio-based plastics (adapted from (Hann et al., 2019)).

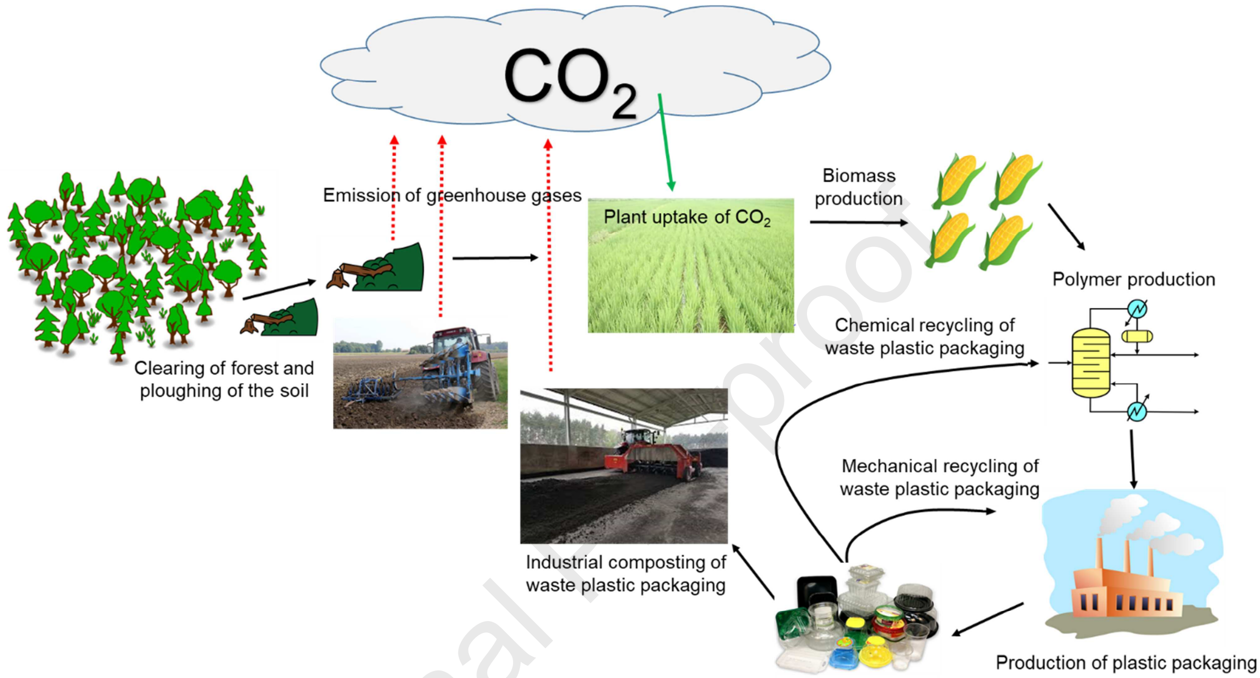

Figure 2. Life cycle of bio-based compostable plastic produced from maize. When first generation biomass is used for production of the packaging, land competition with increased CO_2 emission occurs due to indirect land use changes (ILUC). This induces climate changes and environmental impacts (from e.g. fertilizers, pesticides and use of water).

Tables and captions

Table 1 Examples of food packaging and disposable food contact articles made of different plastics including both bio- and petroleum-based plastics.

Packaging material type	Material*	Applications	References
Bio-based plastic materials	Starch-based polymers	Coffee machine capsules, bottles, disposable tableware and cutlery	(Halonen et al., 2020)
	Cellulose-based polymers	Dried product packaging; films to coat bread, fruit, meat	(Halonen et al., 2020), (Shogren et al., 2019)
	PLA	Cups, bowls, bottles, bags, jars, and films	(Halonen et al., 2020), (Shogren et al., 2019)
	PHA	Composite for different applications e.g. bags for snacks	(Halonen et al., 2020), (Shogren et al., 2019)
	PEF	Bottles, fibers, and films (bio-based alternative to PET)	(Halonen et al., 2020)
	PA	Multilayered structures to provide both strength and toughness in the food packaging.	(Halonen et al., 2020); (Teck Kim et al., 2013)
	PBS	Paperboard coat as direct food contact material.	(Thurber & Curtzwiler, 2013)
	PTT	Bottles and others (similar to PET)	(Ohishi & Otsuka, 2014)
Bio and Petroleum based plastic materials	PP and PE	Similar to fossil-based PP and PE (it is widely used to pack biscuits, snack foods and dried foods)	(Halonen et al., 2020), (Allahvaisi, 2012)

	PET	Beverage bottles, fruit and vegetable trays	(Shogren et al., 2019), (Mutsuga et al., 2005), (Ohishi & Otsuka, 2014)
Petroleum based plastic materials	PVAOH	Coatings and adhesives for paper and board	(Halonen et al., 2020)
	PCL	Food contact material as blends	(Halonen et al., 2020)
	PBS, and PBSA	Disposable cutlery	(Halonen et al., 2020)
	PBAT, PBST	Films and fast food disposable packagings	(Halonen et al., 2020), (Jian et al., 2020)

*Abbreviations: PLA, Polylactic acid; PHA, Polyhydroxyalkanoates; PP, Polypropylene, PE, Polyethylene; PET, polyethylene terephthalate; PEF, Polyethylene Furanoate; PA, Polyamide; PBS, poly(butylene succinate; PTT Poly(trimethylene terephthalate); PVAOH, Polyvinyl alcohol (vinyl polymer); PCL, Polycaprolactone (polyester); PBSA, polybutylene succinate adipate; PBAT, poly(butylene adipate-co-terephthalate); PBST, poly(butylene succinate-co-terephthalate).

Perspectives on sustainable food packaging: – is bio-based plastics a solution?

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Highlights

- Bio-based plastic can reduce climate impact
- Recycling reduces environmental and climate impact