Chapter 5
Circular Bioeconomy: A Path to Sustainable and Climate-Wise (Material) Economy?

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Abstract Circular Bioeconomy – the symbiosis of bio- and circular economies is widely accepted as a solution for ensuring wise and frugal use of bioresources, and provide means to mitigate climate change. In this chapter, we apply circularity concept to scrutinize the use of bioresources and discuss their upcycling circularity potential during and at the end of life of the products and materials. Furthermore, the relationship, including potential synergies and conflicts, between circular bioeconomy and climate change mitigation is studied. The covered sectors include food, packaging, buildings and infrastructure and energy use of regenerated and produced bioresources.

Keywords Circular economy · Bioeconomy · Energy transition · Land use · Sustainability · Biomaterials · Bioplastics · Climate change mitigation · Carbon neutrality · Bioenergy

> Since the global biomass is not an unlimited resource, which applications are the most valuable and sustainable for its use? When biobased resources are used, do we make the economy more environmentally sustainable?

It is widely agreed that Circular Bioeconomy (CBE), the symbiosis of bio- and circular economies, should ensure wise and frugal use of the bioresources and provide means to fight against climate change and environmental degradation. Overall, the concept of circular economy (CE) has become a widely used term in the promotion of sustainable economic activities during the past years (e.g. Circular Economy Action plan (2015), Circular Economy package in (2018), European Commission (2021); Platform for accelerating the Circular Economy (PACE), PACE, WEF 2018). CBE is a part of CE that emphasizes the circulation of renewable resources and products.

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E. Koukios, A. Sacio-Szymańska (eds.), *Bio#Futures*,
https://doi.org/10.1007/978-3-030-64969-2_5

From the environmental sustainability point of view, we are trying to solve two massive global challenges by using biomass: climate change with the reduction of greenhouse gas (GHG) emissions and transitioning our linear economy into sustainable circular operation model that is based on using bioresources.

Yet, the concept of circular economy is argued to be inherently vague and lacks scientific foundation and empirical research to support it (Kirchherr and van Santen 2019; Korhonen et al. 2018). If not evaluated properly, circular activities can backfire in increased emissions and loss of materials and therefore impact nature negatively (Carmona et al. 2017; Zink and Geyer 2017). Thus, circular activities are not inherently sustainable. Each process, material and product should be assessed to evaluate as for sustainability. Furthermore, it is vital to understand that biomass is not an unlimited resource. Even though technologies and different ways of use allow extending the resources available, there is a limit to how much biomass we can use sustainably. Furthermore, there are uses where we cannot replace biomass, most importantly as food and feed, while in other uses, such as energy, there are other alternatives. The crucial challenge to solve is how much biomass we have sustainably available after such vital and necessary uses, and what is the most efficient way to utilize it.

Biomaterials are typically categorized more sustainable than their non-renewable counterparts due to their regenerative nature. However, in many cases replacing a material source with more sustainable one alone is not enough from a lifecycle management perspective. If materials and products are made out of bioresources but are not designed for efficient circularity, their true potential for achieving sustainability is lost.

Our economic system is presently facing large sustainability challenges. On one side we have the Paris Agreement aiming at limiting global warming to well below 2.0 degrees Celsius, which means reducing the global CO_2 emissions by 30% between 2010 and 2030 and reaching net-zero emissions by 2050 (IPCC 2019). On the other side, we have a global linear economy that uses massive amount of virgin raw materials each year, and the extraction and production of these raw materials are fuelled mainly with fossil energy.

Transition from fossil energy resources to clean and renewable ones plays a vital role in reducing GHG emissions and mitigating climate change. In sustainable circular economy, products and materials should be re-circulated into use in a way, which does not degrade the value of the product or material and does not use excess energy or virgin materials in the re-circulation processes. Inevitably, complete avoidance of energy use is never possible. The outmost layers of circularity operations are often the most energy intensive. Thus, keeping products in longer use and avoiding unnecessary recycling contributes to climate change mitigation.

However, there is a limit to how many times materials and products can be re-circulated. Some materials preserve value better than others in recycling processes, even in advanced processing. This is not only due to design aspect but also due to the material type and properties. Design for circularity can extend the lifetime of the material but only to a certain point. Eventually all of the materials reach their very end-of-life, after which there is no longer value in re-circulating them back into use as materials due to severe downgrading and loss of critical properties. Or at this stage recycling processes may be unsustainable compared to value achieved, for instance, due to requirement of extensive energy or use of chemical in the process. Therefore, the most benefit may be gained by re-circulating material into energy. In some cases and for some material streams, energy recovery can be the best option also from the environmental sustainability point of view. As materials lose value in properties during use phases and reprocessing, the heat value might not be the same compared to virgin material. For example, when used for bioenergy, more energy might be gained from primary biomass. Some of the downgraded cast-off materials have less energy value at their end-of-life; despite this their use for energy is welcomed in replacing the primary biomass for energy.

In 2017, the global economy needed 100.6 Gt of materials for covering key societal needs, like nutrition, housing, consumables, mobility, health care, communication and services (Circle Economy 2020). According to forecasts of International Forecast Panel (IFP), the amount is estimated to grow between 170 and 184 Gt by 2050 (IFP 2017). In 2015, from 92.8 Gt input of the total resources entering the global economy, some 51.9 Gt remained unaccounted and were assumed scattered into the environment in form of emissions and unrecoverable wastes. Most of the extracted resources are lost already within the first year of production without any possibility to restore and re-circulate them back into economy. Thus, the challenge of adjusting our economic system within sustainable limit is enormous and requires ambitious mitigation actions across all economic sectors. During the past few years, several countries and regions have launched targets for carbon neutrality. For example, the EU is aiming at carbon neutrality by 2050, which is at the heart of the European Green Deal accepted in 2019. Among Nordic countries Finland has one of the most ambitious climate change mitigation strategies targeting carbon-neutraly by 2035 (Carbon-Neutral Finland 2035 2020).

In this chapter, we apply circularity concept to scrutinize the use of bioresources and discuss their upcycling circularity potential during and at the end of life (i.e. EOL phase) of the products and materials. Furthermore, the relationship, including potential synergies and conflicts, between circular bioeconomy and climate change mitigation is studied. The covered sectors include food, packaging, buildings and infrastructure and energy use of regenerated and produced bioresources. These biomass applications were chosen due to their volume, importance and relevance. The role of nutrition in use of biomass is self-evident, whereas packaging plays a vital role in making the food sector more frugal and sustainable and decreasing its contribution to climate change. In addition, demand for plastic packaging is growing tremendously due to increased consumption, increase of population and especially rise of middle class. Due to the intense increase in predicted plastic production, the emissions are also predicted to grow significantly. Infrastructure is one of the largest contributors to climate change, in which the use of bioresources is seen as a part solution for cutting down the emissions. Presently, biomass dominates the use of renewable energy (WBA 2019). We start the discussion with bioenergy since biomass use for energy is the most conflicting one within the circularity concept.

Although globally different strategies for the use of biomass pursue sustainability and green growth, they overlap and may be conflicting with each other depending on what applications for biomass are promoted. By exploring these sectors and applications where biomass is used, we put an emphasis on circularity and emissions and discuss critically if the replacement of unsustainable materials with bioresources makes the (material) economy environmentally more sustainable.

1 Conflicting Uses of Biomass and the Potential for Sustainable Circularity

The agriculture, forest and other land (AFOLU) is responsible for about 25% of the global net anthropogenic emissions (IPCC 2014). The emissions stem mainly from deforestation and agricultural emissions from soil and nutrient management and livestock. The AFOLU sector accounts for about a quarter ($\sim 10 - 12 GtCO_2eq / yr$) of net anthropogenic GHG emissions (IPCC 2014). In order to get an understanding of how efficiently biomass works in climate change mitigation, it needs to be studied in relation to a reference situation where less biomass is harvested for energy (Heinonen et al. 2017). For agricultural biomass, the computational implications are relatively clear: the rotation is fast and the harvested biomass grows back quickly. Potential loss of carbon takes place either through land use change when new fields are cleared or through loss of carbon from soil. In the slow-growing forests, such as boreal forests, impacts of harvesting need to be calculated by comparing scenarios with different levels of extraction of forest biomass.

The assumption considering biomass a zero emission source is often based on the misunderstanding of the UNFCCC greenhouse gas emission inventories in which biogenic carbon emissions from energy production are considered zero (Wiloso et al. 2016). This is because the emissions from carbon stock changes are taken into account in the land use sector. Thus, they are not considered zero but are accounted for in land use instead of energy.

In addition to emissions from land-use changes, climate impacts of agricultural biomass production stem from production of fertilizers, energy and other inputs needed in growing, collecting and processing the biomass, and emissions from soils resulting from fertilizer application (e.g. N2O emissions). Furthermore, the role of indirect land use change (ILUC) in connection to bioenergy production has been widely recognized (e.g. Plevin et al. 2010; Wicke et al. 2012). ILUC refers to a change in land use elsewhere because direct land use change (LUC) causes either displaced production of agricultural food, feed or fibres in order to cover for the existing demand or because more land is brought into agricultural production due to price increases (Gerssen-Gondelach et al. 2017). Actions have been taken to mitigate ILUC as a result of bioenergy production from agricultural biomass such as the limitations on high ILUC risk biofuels in the EU Renewable Energy Directive, but its complete elimination is very difficult. Hence, the role of wood biomass in climate change mitigation has gained a lot of attention during the past years. Wood biomass is, when sustainably grown, a renewable resource and largely recyclable and reusable material. Only a small fraction of wood products cannot be re-used or recovered directly (e.g. hygiene paper or contaminated wood material). However, the role of forest biomass in climate change mitigation is more complicated (Fig. 5.1). In the forests, wood acts as carbon storage. It is crucial to manage and harvest the forests in a sustainable way. Furthermore, the present wood product mix typically consists mainly of short-lived products and energy. With this type of applications of wood, positive climate impacts cannot be obtained for at least decades (Seppälä et al. 2019b).

The idea of carbon neutrality of forest biomass use is based on the notion that in sustainable forestry, the extracted wood will eventually grow back and re-absorb the carbon that was released. As forests are slow-growing, in particular boreal forests, it takes from decades to even centuries for it to absorb the released CO_2 from the atmosphere. The so-called climate debt from the utilization of forest biomass for energy stems from exactly this: as biomass is taken from the forest, an unavoidable reduction in forest carbon stock is caused, compared to a situation where biomass is not taken. When biomass is removed from the forest, the amount of carbon stored in the forest decreases. Furthermore, had the forest not been harvested, it would have continued to absorb more carbon, thereby acting as a carbon sink – a phenomenon often referred to as foregone sequestration (e.g. Koponen and Soimakallio 2015) Fig. 5.2. In the longer term, more intensive harvesting leads to lower carbon stock on a landscape level than the scenario with less harvesting.

However the impact is not straightforward: the overall carbon balance of wood use is determined by such factors as the actual use of the harvested wood products,

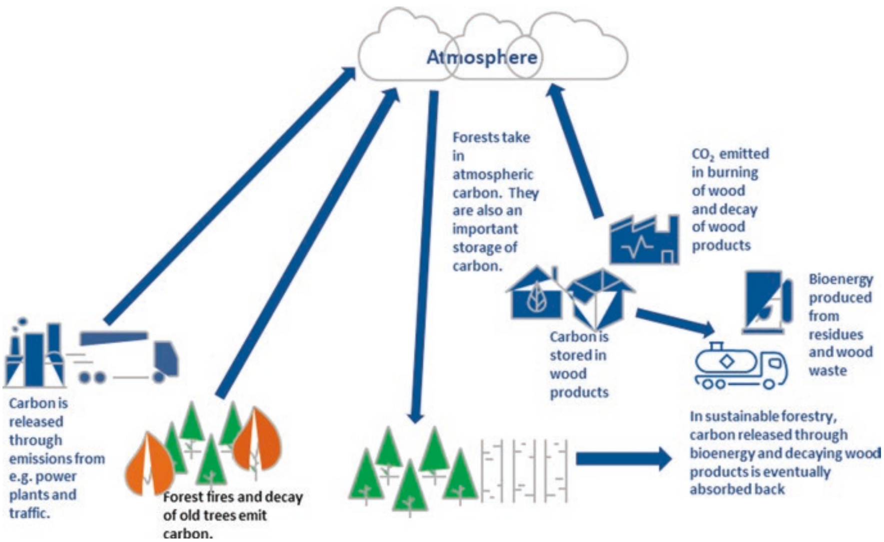

Fig. 5.1 Forests affect climate in many ways

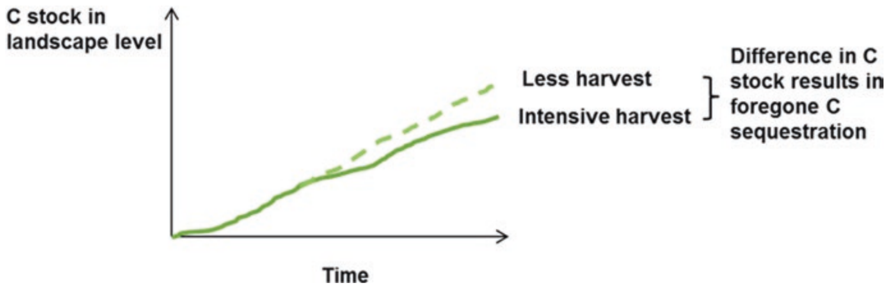

Fig. 5.2 Illustration of a comparison between intensive and less intensive harvest scenarios: carbon stock (C stock) increases in both scenarios but more in the "less harvest" scenario. (Koponen et al. 2015)

how long they remain in use and what kind of products they replace (substitute) in that use (Fig. 5.2). This means that carbon loss in forests could be compensated through production of long-lived products with high wood content, such as solid wood products used in wood buildings that could also substitute for emissions from other fossil-intensive materials such as steel, glass or concrete (Gustavsson et al. 2006; Pingoud et al. 2010). Displacement factors have been presented to express the efficiency of using biomass to reduce net greenhouse gas (GHG) emission through quantifying the amount of emission reduction gained per unit of wood use (Sathre and O'Connor 2010). Yet, these displacement factors typically do not consider the lost carbon sequestration in the forest.

In order to take into account the lost carbon sequestration in the forest, Seppälä et al. (2019a) have introduced "required displacement factors (RDF)", which depict the displacement factor needed in order to achieve zero $CO_{2eq.}$ emissions from increased forest utilization over time in comparison to a reference harvest scenario. Their results indicate that in Finland, which has large forested areas and important forest industry, compensating a 30% increase in annual harvest would necessitate an RDF of 2.4 tons carbon per each carbon ton in the wood-based products and fuels obtained from the increased harvest in 2017–2116 (Seppälä et al. 2019a). Most of the wood uses do not provide such high displacement factors. According to Kunttu (2020), high enough displacement factors could be achieved with only few products, e.g. textiles produced from pulp and wood-based plastic composites.

2 Bioenergy

Currently, bioenergy is the largest renewable energy source globally with an estimated share of 70% of all renewable energy consumption (WBA 2019). At the same time, the use of biomass for energy is in conflict with the principles of circular economy and in many cases also with climate change mitigation. Energy production is a one-off use of biomass, while there are other more sustainable uses of biomass that are longer lasting by binding carbon for longer periods of time and especially in replacing non-renewable materials that have high environmental impact. Since the amount of biomass available is limited by various other factors, such as other land uses, its use for energy production reduces opportunities for valuable non-energy uses. Regarding GHG emissions, the role of biomass is not straightforward because its impact on emissions is dependent on various land-use related phenomena such as climate debt and foregone sequestration that were discussed in the previous section. Direct emissions are comparable with those of fossil fuels, with CO_2 emission factors of approximately 110 g CO_2/MJ for solid biomass fuels, 70–80 g/MJ for biofuels and 50–60 g/MJ for biogas (Statistics Finland 2020). The overall GHG balance of biomass can vary widely depending on the type of biomass, the location it is grown (e.g. need of fertilization, growth rate, transportations needed) and how the fuel is processed (e.g. how much energy and other inputs are needed in the processing).

Other than GHG emissions from biomass are roughly comparable to the combustion of other chemically similar fuels. Pollutants such as nitrous oxides and particulate matter can be a local health and environmental problem, in some cases a serious one. Typically pollution-related health problems can be severe with small-scale combustion of fuels in densely populated areas. This is an issue in many developed countries where firewood still has a role in heating. For example, in Finland small scale burning of firewood causes approximately 200 excess deaths a year from a population of 5.5 million (Savolahti 2020). However, the problems are much more severe in the developing world, where in some localities, such as much of sub-Saharan Africa, the traditional use of biomass for heating and cooking is still the dominant form of energy use (WBA 2019). Moreover, the health impacts are often paired with other harmful effects such as heightened risk of fire and overuse of local resources. Some of these detrimental impacts will be alleviated with growing incomes and people gaining access to other energy carriers. However, this development will bring along other environmental and social burdens unless it is done relying on sustainable energy sources.

The world energy market still relies heavily on the use of fossil fuels, which is the main contributor to climate change globally. Even though the overall amount of renewables is increasing, its growth rate is not fast enough to meet the simultaneously growing global demand for energy. During 2016–2017 the primary net energy supply of fossil fuels had increased more than the supply of renewable energy sources that was lacking behind (0.7%). The increase of 1.5% in 2016–2017 in total primary energy supply was matched by coal, oil and natural gas. In 2017, combined (oil, oil products, coal and gas) fossil fuels still dominated the global energy mix with the share of 80%, and the renewables accounted for 17.7% in the final global energy consumption. The same year, among renewable energy sources, bioenergy accounted for 70% of the renewable energy consumption. The relative share of bioenergy has been declining slightly a fraction of a percentage point (0.5–1.0%) annually due to decreased use of traditional biomass sources that outpace the simultaneous growth of modern uses of bioenergy (WBA 2019). In absolute terms the use of bioenergy nevertheless is growing.

Most analysts are forecasting growth for the use of biofuels. For example, IEA forecasts a growth of 40% for total use of bioenergy globally by the year 2040 (IEA 2019), whereas Rogelj et al. (2018) foresee on average a tenfold increase in biomass use in electricity generation by the year 2050. The increases in these scenarios are in part driven by the fact that combined with CCS and CCU, bioenergy offers countries the unique ability to actually reach negative CO_2 emissions and contribute to international climate goals.

Globally, forestry is the largest contributor to the bioenergy mix. It accounts for more than 85% of all the biomass used for energy purposes, including forestry products like charcoal, fuelwood, pellets and wood chips. Recently the use of agriculturally produced feedstock for the production of liquid fuels such as ethanol and biodiesel has grown fast, roughly doubling in volume from 2008 to 2018 (REN21 (2019): Renewables 2019 Global Status Report). It now represents 8% of all bioenergy use and 3% of all energy for transport globally. The relatively high carbon footprint of farming however means that these fuels tend to be far from climate neutral, roughly halving the carbon emissions compared with similar crude oil-derived fuels (UK Department for Transport (2008): Carbon and Sustainability Reporting Within the Renewable Transport Fuel Obligation).

There are, however, still high-yield sources of bioenergy that are far underused. In terms of major energy content, IEA has identified biomass production on marginal lands (potential of 60–110 EJ), residues from agriculture (15–70 EJ), forest residues (30–150 EJ), dung (5–55 EJ) and organic wastes (5–50 EJ) as ones that do not interfere with existing agriculture and forest harvesting for other purposes (IEA 2007). Even though their potential is large, also in this case that same potential competes between application for energy and longer lasting material use.

Growing use of biomass for energy is difficult to reconcile with the concept of circularity. To resolve the conflicting demands for biomass in energy and other uses, the clearest path forward is to grow the share of other renewables such as solar, wind, hydroelectric, geothermal, ocean, hydrogen and nuclear. This can help to reduce the overall share of biomass, especially primary forest biomass that is being used for energy production. Bioenergy demand could be also partially met by certain products and materials that have reached their very end-of-life, and are more valuable and sustainable for energy application; although this kind of replacement requires massive optimization of resources and the volume of biomaterials reaching their very end-of-life may not be sufficient to meet the demand. In addition, there may be limits to this kind of optimization to match the local and temporal needs.

Despite this, it is evident that the shift to reducing primary use of biomass for energy will not happen overnight. Bioenergy has some benefits that make it ideal to certain roles at least for a transition period on the path to a more sustainable energy system. It is, for example, a promising option to balance variable energy sources, since it is a flexible and storable resource (Hakkarainen et al. 2019). In certain uses, such as heavy vehicles, ships and aircraft, it is difficult to replace liquid fuels, making biofuels often the most viable renewable replacement. Moreover, when biomass is used for energy production, carbon capture and utilization (CCU) technologies should be applied to re-circulate the emissions into raw materials, and further into new products and chemicals. Currently, the scale up and market uptake of CCU technologies is challenged by energy-intensive CCU processes. On-going research in the CCU field is aiming at finding sustainable and profitable solutions for CO_2 re-circulation technologies. When resolved, use of bioenergy combined with CCU can offer the triple benefit of renewable energy, CO_2 removal from atmosphere and renewable chemical products created from the flue gasses.

3 Nutrition

"Food is the single strongest lever to optimize human health and environmental sustainability on Earth. However, food is currently threatening both people and planet." These emphatic words begin the summary report written by experts of the EAT- Lancet Commission (EAT-Lancet Commission 2019). We live in the world of growing human population leading to increasing need for food and increasing challenges in the primary production of food raw materials, both threatening the food security. This dual problem calls for radical and systemic transformation in the global food system that can be supported by circular bioeconomic solutions, data technologies and digital platforms. The EAT-Lancet Commission's message is clear: Agriculture and fisheries must not only produce enough calories to feed a growing global population but must also support environmental sustainability (EAT-Lancet Commission 2019). This will be, self-evidently, realized firstly by shifting towards plant-based food, particularly in high and mid-income societies. In the second wave, healthy microbe biomass and specialty proteins, e.g. meat, milk or egg proteins, produced by microbial hosts in controlled environments may appear to enrich the plant-centred diet flavoured perhaps by means of augmented reality.

We continuously use more resources than what the planet is capable of producing. Overall global material extraction has multiplied tenfold since the beginning of the twentieth century. It is claimed that global socioeconomic material stocks rise 23-fold over the twentieth century and require half of annual resource use (Krausmann et al. 2017). The global extraction of biomass in 2017 was 24.6 billion tonnes, 21.3 billion tonnes of which was used for food processing (Circle Economy 2020). Food and feed together account for the majority of global biomass demand, crop production (sugar cane, maize, wheat, rice paddy, potatoes together) 5 billion tonnes, meat 340 million tonnes (Weindl et al. 2015), fisheries and aquaculture 170 billion tonnes (amounts approximated from FAOstat data from 2017 (FAO 2020a). It is estimated that about one third of food is lost or wasted throughout the agro-food chain, in the high- and middle-income societies mostly in the consumption stage and in the lower-income societies in the earlier stages of the food production value chain (FAO 2020b). This is not only wasting food raw materials and food itself, but also pure water, energy and soil, consequently increasing emissions to the environment.

Agriculture, fishery and aquaculture, including forestry, have significant impacts on water, soil, air quality and biodiversity. Increasing need for food and energy increases pressure to further expand extraction of both abiotic and biotic resources from the earth crust stretching the planetary boundaries (Steffen et al. 2015) to the utmost. Besides, agriculture is the largest user of the world's freshwater reservoirs (UNESCO 2020). This, rather chilling, situation calls for solutions that a circular bioeconomy can offer. These solutions must also be sustainable, which is not self-evident or straight forward, when the nexus of food, land, energy and water is to be mastered.

In bioeconomic operational and business models, supply and demand may conflict when it comes to offering to the societies healthy food, biobased materials and bio-energy, production of which necessitates water (potable in case of food), soil and arable land. A sustainable CBE maintains the value of the extracted natural resources by cascading the resource use (EEA 2018) and creating solutions by which resources are kept in value-sustaining use as long as possible and recycling them back into use at the end-of-life. In addition to food, the agro-food chain losses and waste have important implications for resource insufficiency in a broader sense causing ultimately poverty and limiting economic growth.

In the early stages of the agro-food chain (primary production and post-harvest), balanced land-use between crops cultivation and animal farming as well as wise use of agro-industrial side streams and residues is improving. A recent FAO study states that 86% of livestock feed (forages, crop residues and side streams) is not suitable for human consumption and edible grains account only for 13% of the global livestock dry matter intake (FAO 2020c). A decade ago about a half of the world's crop energy content was eaten directly by people, the rest being divided to livestock and energy or other industry purposes (Cassidy et al. 2013).The researchers also reported that crop energy content used for biofuel production increased fourfold between the years 2000 and 2010, from 1% to 4%, representing a net reduction of available food globally.

The transition to wasteless and loss-resistant food and agriculture will happen through harnessing broadly possibilities offered by data technologies, artificial intelligence, automation, novel food raw materials and production technologies as well as genuinely closing agro-food material, side stream and waste flows enabled e.g. in integrated production systems (Lantto et al. 2018).

Food production is predicted to move gradually from farming lands and natural waters to compact closed-loop systems that minimize the need for mineral fertilizers, feed for livestock, clean water and energy. The smart food production factories will be closely integrated to farming systems driven by advanced automation. In addition, coupling farming and food production systems with their process digital twins for constant and accurate assessment of the production and process situations, optimal efficiency and reliability can be achieved (Poutanen et al. 2017). It is also the way to manage the food production and supply chains more efficiently. Integrating platform economic solutions to food distribution will pave the way to reduced waste generation enabling shorter and more efficient food supply chains. This necessitates availability and sharing of accurate data, which is more easily said than done due to currently prevailing operational and business models that favour sub-optimization of operators in the chain.

A scalable and convertible closed-loop food factory (based on, e.g. recycled aquaculture, aquaponics or hydroponics systems) will enable resource efficiency and independence from regional and climatic boundaries. It will need data and sensor technologies, smart automation and robotics, water purification, chemical and food technologies as well as expertise in integrating, optimizing and making compatible with each other diverse production systems, such plant, insect and algae cultivation and aquaculture. Outfitting a close-loop food by a clean energy supply system (e.g. photovoltaic systems for electricity), anaerobic digestion of the factories' biowaste for energy carriers and recycled fertilizers and a collection system for rainwater and condensed atmospheric water, environmental sustainability and overall resource efficiency can be improved and independence from external factors minimized.

Sustainability of the first half of the agro-food chain (primary production, post-harvesting and food processing) can be improved by the abovementioned integrated closed-loop solutions. The latter half of the chain is taken care of by the retail, and particularly consumers who play the most focal role to what direction the agro-food chains will eventually develop. By changing purchasing and consumption behaviour towards favouring non-meat food and accepting new protein and other nutrient sources, for example, insects or microbes, consumers can affect the whole agro-food chain consequently improving sustainable use of natural resources and sufficiency of food.

The bulk of the living matter is composed of elements and compounds found in the atmosphere. Instead of being restricted to selected locations, atmospheric resources are available everywhere. Sustainability of the future food system could be achieved by taking into use atmosphere and industrial exhaust gases as raw material resources. The atmosphere is a notable reservoir of CO_2 together with other essential elements and compounds such as nitrogen, oxygen and water. Comeback of the resource sufficiency will rely on technological innovations that will enable the use of agricultural and industrial effluents in addition to the atmospheric components as raw materials (Lantto et al. 2018; Lehtonen et al. 2019).

Green plants are naturally efficient in transforming CO_2 to sugars and other essential nutrients. The more we get our nutrients from plant sources the better is the food security globally. Shift towards plant-based diets is essentially important in the high- and middle-income societies. One of the consequences of the progressive climate change is the productivity loss in many agricultural regions in the world, but food needs to be produced in increasing amounts. Secondly, CO_2 should be captured and utilized also by other means than via photosynthesis of plants. Nature's immense synthesis power should be harnessed to support bringing back its resource sufficiency in order to secure sufficient amount of nutritious food for all. Several microorganisms exist that convert CO_2 and N_2 by nature to components the cells need for growth and multiplication. To our knowledge the food safety status of these microbes has not been studied or determined. Of course, ability to utilize both CO_2 and N_2 as sole carbon and nitrogen sources for growth can be engineered to an edible microbe. This possibility has to wait for permissive political decision-making and regulative environment before genetically engineered microbes could be used as food factories to produce all nutritive components a healthy human diet requires.

By utilizing the ability of microbes, whether natural or genetically modified, to fix gaseous nitrogen (N_2) and CO_2, food production could be decoupled from agriculture and aquaculture. The environmental impacts are minimized. Food production would be no longer dependent on any specific ambient temperature, humidity, light, soil type or region, and as such a food source can also be provided in locations that suffer from lack of arable land or soil due to the consequences of the climate change and unsustainable agricultural practices. Microbial cells as "factories" to produce animal proteins for food use are already seen potential from the commercial perspective.

Food production could take a giant leap forward by shifting towards plant- and microbe-based diets and taking into using gaseous components directly from air or human and industrial operations. Meat and meat-based food would be the loser in this battle. When feed protein is converted to meat protein, the most of it is lost to maintain the bodily functions and growth of the animal. An average of 3 kg of cereals are needed to produce 1 kg of meat at global level (FAO 2020c). Fresh meat and fish contain about 75% of water, while grains, nuts and peas a lot less. In addition, meat and fish products are very prone to spoilage in warm temperatures. These facts are crucial when packaging is considered for storage and transportation.

4 Plastic Packaging – The Villain – Decreases Food Sectors' GHG Emissions

Packaging is crucial, yet it is a controversial topic as the main material used for it – plastic – is accumulating as waste in the environment and especially oceans. The negative environmental impacts have set off trends to go packaging-free or even avoid plastics all together. However, plastics are not the bad guys – certainly there is a lot to fix in the current linear economy that is known for single-use plastics, but the answers lie in sustainable circular economy. To further tackle the contribution to climate change, it is immensely interesting to look at circular bioeconomy solutions.

If global food waste would be a country, it would be the third biggest GHG emitter – 30% of food produced globally is lost or wasted annually (FAO 2013). A study by Zero Waste Scotland calculated that in 2016, the carbon footprint of food waste from Scottish households was almost three times that of plastic waste collected (Zero Waste Scotland 2018). Food packaging is a crucial plastic application as it reduces food waste by preserving and protecting the food. Food waste is already a major concern because of its direct emission contribution to climate change, and it would increase even further without proper packaging. In Fig. 5.3, some examples are presented to highlight the impact of plastic packaging on the shelf life of different food products (FPA 2014).

Produce	Cucumber	Zucchini slices	Banana (distribution)	Cherries	Pear	Fish	Cheese	(Whole) Chicken
Shelf life: no packaging with plastic packaging	3 days 14 days	1–2 days 4–6 days	15 days 36 days	14 days 28 days	7–10 22–25	7 days 12 days	190 days 280 days	7 days 20 days
Difference	11 days	2–4 days	21 days	14 days	15 days	5 days	90 days	13 days

Fig. 5.3 Comparison of shelf life of different food products with and without plastic packaging. (Source: Tenhunen & Pöhler 2020)

The first task of the packaging is to serve the product, focused on preservation and protection, and these requirements for the packaging are based on the product. If the global diet would shift from mainly fresh meat and fish to dry grains, nuts and peas, the requirements for their safe preserving would be less intensive. A piece of meat today could typically be packaged into vacuum with multilayer and multimaterial nonrenewable virgin fossil-based plastic packaging – this type of packaging is challenging if even possible to recycle due to the fact that the laminated multilayers are not separable. Packaging of dry grains on the other hand could be made out of fibre-based packaging that is recyclable multiple times.

The packaged food products are expected to ensure long logistics chains from factories to intermediate storage and eventually shops; in many cases food is shipped from countries and continents to others. In addition to preservation properties, the packaging must be presentable and market the product accordingly. Today, we have a wide range of advanced packaging that are many times competing with each other; glass, wooden, paper and cardboard, composite, metals and fossil- and biobased plastics (Emblem & Emblem 2012).

The food production, logistics and sales of food have changed significantly as mass production of plastics began in the 1950s. Plastics have been designed for optimum product performance in a linear economy – they have been designed for single-use and low-cost production. In addition, plastics have great barrier properties, they are light-weight and easily mouldable into different shapes and sizes, which has made the mass production of plastics effortless. Linearity aspect of plastic products makes it challenging to switch to circular practices – the variety of materials is huge, and there is lack of infrastructure for collection and processing – furthermore, the markets for recycled polymers are still developing.

What further makes the shift to circularity challenging is the massive volumes of generated and used plastics. In 2018, global plastics production was almost 360 million tonnes and almost 62 million tonnes in Europe. Packaging represents the largest end-use markets in Europe – approximately 40% of all plastics produced are used for packaging (Plastics Europe 2018). The production of plastics is expected to increase even up to fourfold by 2050 (Fig. 5.4).

Developing societies and especially the rise of middle class is expected to have a massive impact in the increased predictions of future plastic productions. In the Western Europe and North America, average of annual plastic consumption per capita is around 100 kg, where in Asia it is only around 20 kg/capita/year. To

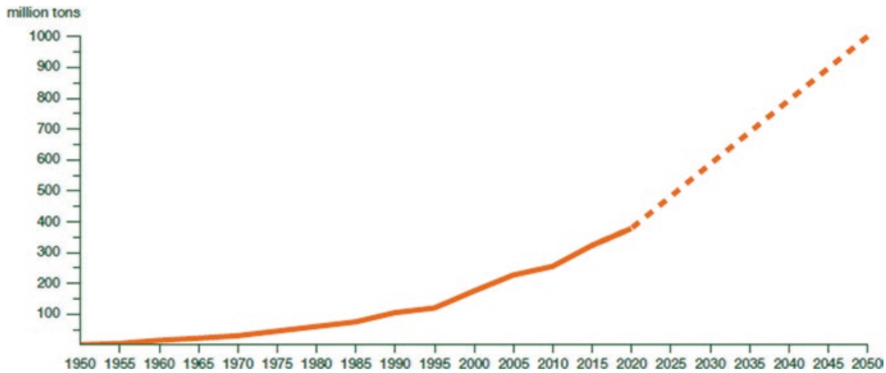

Fig. 5.4 Global plastic production volume development 1950–2050. (Source: Tenhunen & Pöhler 2020)

elaborate on the impact of developing societies and rise of middle class, in India, the overall plastics consumption has increased over 40 times since 1990 to 2017 from 0.4 Mt/year to 16.5 Mt/year (Babayemi et al. 2019).

Plastic packaging has positive impact on lowering food sectors emissions; nevertheless, plastic food packaging has an emission-intensive life cycle. As plastic packaging has a relatively short-term life cycle in a linear economy, the recycling of plastic food packaging is challenging and still not a well-established practice globally. Originally, linear economies were developed without a recycling capacity, resulting in our environment becoming a waste reservoir. Today's make-use-uncontrolled dispose economy of plastics has resulted in plastic waste leaking into nature and polluting the environment – humans, animals and living organisms on land and in the sea are susceptible to the effects of plastic waste in nature. Globally, 1.5–4% of global plastics production ends up in the ocean annually. The estimated release of microplastics in the environment in the EU is 75,000–300,000 tonnes each year (European Commission 2019). The economic viability of agriculture, fishery and other livelihoods is vulnerable due to the effects of plastic waste.

Furthermore, plastics contribute to climate change during several stages of their life cycle, e.g. during manufacturing, end-of-life management by incineration and even as pollutants in the environment as the waste begins to degrade. The current GHG emissions from plastics life cycles threaten our ability to meet global climate targets. Today, the GHG emissions from plastic production and incineration are more than 850 million metric tons, which is equal to the emissions from 189 (500 MW) coal power plants and very close to the total emissions of greenhouse gases in Germany in 2019 (858 Mt) (Clean Energy Wire 2020; Hamilton et al. 2019). With the current trajectory, by 2050 the cumulative emissions of the plastic life cycle will be over 56 gigatonnes CO_2eq, which is 10–13% of the global carbon budget calculated based on the 1.5 °C target (Hamilton et al. 2019). Recycled and renewable raw materials, such as biomass or carbon dioxide, will become even more important feedstock streams for future plastics in a circular plastics economy to further mitigate the impact to climate change.

Currently, polymers are mainly produced from fossil sources such as crude oil. Bioplastics represent approximately only 1% (2.1 Mt) of plastics produced. For biobased plastics, packaging is the largest field of application which accounted for more than 53% (1.14 Mt) in 2019. In 2019, material use took up 2% of the global agricultural area; from this biobased plastics took up approximately 0.016% (Fig. 5.5) (Bioplastics 2019). It has been calculated that if all world-wide fossil plastics (2015) would be produced from biomass, the demand for feedstock would be 5% of the total amount of biomass produced and harvested each year (Martien van den Oever, Karin Molenveld, Maarten van der Zee 2019). This does not take into account the use of side and waste streams. What would 5% mean in terms of taking up land from food and feed? Is it sustainable to utilize such agricultural land for material production? Instead, the priority should be in food production and in side and waste streams utilized for materials as well as utilizing wood biomass from forests. One of the challenges with food packaging is legislation, e.g. EU's current legislation allows mainly only the use of virgin material to be used as contact material for food applications (European Commission 2008). Recycled material, if collected as a mixture, contains contaminants like bio- and food waste, not applicable again as food packaging. An exception is PET bottles that can be reprocessed for bottles again due to separate collection systems and specific recycling process. Safety is something that cannot be compromised – for this reason it requires a lot from R&D&I to develop the means to process food packaging waste back into food packaging, to close the loop. Furthermore, the pressure is on to quickly develop reliable solutions. One interesting and promising solution is (thermo)chemical recycling, where the plastic waste material is recycled back to feedstock building blocks, monomers.

Plastics consists of polymers and additives and are typically named according to the polymers they contain. Polymers are processed and mixed with additives to help with processing or improve product performance such as plasticizers, flame

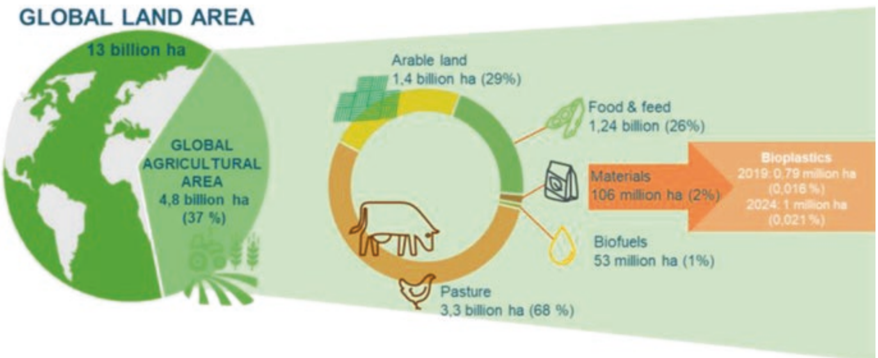

Fig. 5.5 Land use estimation for bioplastics 2019 and 2024. (Source: European Bioplastics 2019)

retardants, antioxidants, light and heat stabilizers, and pigments. Fossil-based plastics as a material, the polymers and a variety of additives, and food packaging applications are high performing and well optimized for the use phase – they have been developed and researched for a relatively long time compared to biobased plastic alternatives. In addition to biobased plastics, fibre-based solutions like carton, packaging papers, container and corrugated board are important packaging applications. The food packaging sector is one of the main sectors driving the growth of fibre-based packaging (Paper Industry World 2015). There is no doubt that the different packaging materials are competing with each other. Furthermore, we are seeing hybrid packaging materials where fibre-based and plastic materials are combined together. It is also important to note the difference in biobased materials and biodegradable materials – biobased materials do not mean that the material is biodegradable. Also, having biobased solution is not necessarily circular. The critical issue is how the material can be recycled back into materials without losing or minimizing value. Is it the best use of materials if they are biodegraded after one use? Or is it in this case, just a linear single-use biodegradable product that is only a bit better than its fossil-based non-biodegradable counterpart? For achieving the optimal solution, reuse and recyclability should be carefully assessed, and biobased and biodegradable products should be also designed for re-circulation.

The wide variety of available materials used in different packaging is making the recycling of these materials challenging. The challenge lies in getting high-value and quality recyclates from a very heterogeneous mixture of packaging waste. Smart sensor-based separation processes would assist in solving the challenge of heterogeneous packaging waste, but as the typical recycling infrastructure relies extensively on manual identification and separation, intense investments are needed in R&D and infra to support circularity. Another difficulty, experienced with especially biobased plastics, is that the volumes of biobased plastics are not sufficient enough to actually recycle them. Bioplastics are faced with the harsh reality that even though they are recyclable, they do not get recycled.

The shortcomings and implications of plastics have caused the regulatory framework to change and tighten quickly. For instance, EU has set ambitious policy measures and targets for all the packaging to be 100% recyclable, reusable or compostable by 2030 in the EU (European Commission 2019). Furthermore, in the EU there are set recycling targets for plastic packaging: 55% by 2025, 60% by 2030 and 65% by 2035 (European Commission 2018). The pressing climate neutrality targets effect the plastics value chains heavily – the biobased solutions are one of the key answers in unlocking the climate neutral plastic value chains.

5 Infrastructure: Wood in Long-Lived Products and Structures

Carbon loss in forests could be compensated through production of long-lived products with high wood content, such as solid wood products used in wood buildings that could also substitute for emissions from other fossil-intensive materials such as steel, glass or concrete. In 2017, of the total global material inputs of 100.6 billion tonnes, 48.0 billion tonnes were added to long-term stock, like machines and infrastructure (Circle Economy 2020). From the existing long-term stocks 17 billion tonnes of materials were removed the same year, making the remaining net addition 31 billion tonnes (Circle Economy 2020), resulting in the largest use of material resources. Growing economies and urbanization will even further increase the share of the raw materials used for infrastructure. Using wood as a construction material can potentially lead to large GHG benefits. In a Canadian study applying dynamic life cycle assessment, it was found that the climate impacts of wood product use ranged between −388 and −1264 kg CO_{2eq}/m^3 wood product in life spans of 50–100 years (Head et al. 2020).

In another study by Gustavsson et al. (Gustavsson et al. 2006), it was found that wood-framed buildings would result in 30–130 kg lower carbon emissions per m2 floor area compared to concrete buildings. They also found that use of wood as building material resulted in much lower emissions than its use as energy. Also Pingoud et al. (Pingoud et al. 2010) found in their study of wood use in Finland that highest climate benefits could likely be received with production of long-lived products that substituted fossil-fuel and energy-intensive materials.

However, in a review of different LCA/carbon footprint standards for building materials and products, Tellnes et al. (2017) found that none of them so far consider the effects of delayed emissions on global warming potential (GWP), an aspect that has been highlighted in emerging scientific methods (Helin et al. 2016). Lately, new methods have been introduced to include the temporal aspect into LCA of long-lived products. There are two groups of these methods: dynamic LCA (DLCA) and the bio-GWP approach (Breton et al. 2018). In DLCA, time-dependent characterization factors are calculated to assess the dynamic LCI for any given time horizon (Levasseur et al. 2013). In principal the method is applicable to any impact category, but it has mainly been used for global warming, based on the concept of radiative forcing.

Further challenge in compensating for carbon loss through long-lived products is that typically only part of the biomass is usable in products with long lifetime, which limits its contribution to climate change mitigation and circular bioeconomy. Thus, more research is needed about the potential of long-lived products in mitigating the climate change.

6 Final Words

Bioeconomy emphasizes the use of biogenic feedstocks, mostly forest and agricultural-based, and their components to end products that are mostly food, feed, energy, chemicals, textiles, packagings and paper. It can be considered to belong under the umbrella of circular economy in a sense that it focuses on using biogenic rather than fossil-based feedstocks to produce and manufacture products, but so far it has not emphasized reuse or recycling aspects of the biobased products well enough. Up to now, use of biomass has not always been neither circular nor sustainable. Thus, these two economy models alone are not the answer to sustainability. Use of biomass for each application discussed in this chapter requires careful calculations to avoid mistakes in the evaluation of sustainability of biomass use.

The use of bioresources is generally justified due to regeneration of needed resources compared to non-renewables, amount of embodied carbon, needed energy for recirculation processes and as carbon reservoirs. Food sector is the most crucial application of biomass which should be secured in the first place. Alongside this, packaging plays a prolonging and preserving role in food sector that has significant emissions and potential for decreasing emissions if biobased materials are used sustainably and designed for circularity. Globally, infrastructure has substantial role in emissions, and expanding urbanization is expected to grow the amount of emissions even further due to extensive amount of material input to long-lived stocks. Wood biomass has potential in contributing to GHG emissions positively, but its use and evaluation should be studied further.

Presently, biomass dominates the use of renewable energy (WBA 2019). Even though biomass is not a carbon-free energy source, it is renewable when sustainably used, and its role in the transition to an energy system based on carbon-free energy sources can be justified. On the other hand, use of valuable biomass, especially primary use for energy, fights against the principles of material circularity – cascading where raw material should be kept as material and used in a way which preserves value and enables re-circulation. In the future, bioenergy could be, for example, a promising option to balance variable energy sources, since it is a flexible and storable resource while the focus should be on increasing the share of other renewable energy sources.

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