Biobased Drop-In Polymers, Polyolefins

Marie-Louise Lagerstedt Eidrup, Jonna Hynynen, Maria Pettersson
Chalmers Industriteknik

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Chalmers Industriteknik
Sven Hultins plats 1
412 58 Göteborg

www.chalmersindustriteknik.se
Org.nr 857204-7713

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Executive summary

Plastics are essential materials in the modern economy due to their versatility, performance, and cost-effectiveness. However, the dependence on fossil-based raw materials has raised environmental concerns, driving interest in renewable, biobased alternatives. Among these, biobased drop-in polymers—chemically identical to their fossil-based counterparts—offer a promising solution, as they seamlessly integrate into existing production, processing, and recycling systems.

Despite their potential, biobased drop-in materials face significant challenges, including high production costs, limited availability, and ongoing debates about their true environmental benefits. Current solutions rely primarily on sugar- and carbohydrate-rich crops such as sugarcane, corn, and wheat, raising concerns about land use competition with food and feed production. As a result, utilizing secondary raw materials from forestry and agricultural by-products is emerging as a more sustainable pathway.

The long development cycle of new materials—often spanning 15–20 years—poses an additional barrier to widespread adoption. Meanwhile, well-established fossil-based plastics benefit from a century of technological refinement, optimized supply chains, and a growing recycling infrastructure. Overcoming these challenges will require breakthroughs in material science, policy support, and increased willingness among industries and consumers to invest in sustainable alternatives.

While biobased drop-in plastics represent an important step toward reducing fossil dependency, they are not a standalone solution to plastic pollution and broader environmental concerns. Instead, they must be complemented by improved recycling, material efficiency, and a more strategic approach to resource utilization. The future of bioplastics depends on balancing sustainability, economic viability, and scalability within the existing industrial landscape.

Svensk sammanfattning

Plast är väsentliga material i den moderna ekonomin på grund av sin mångsidighet, prestanda och kostnadseffektivitet. Beroendet av fossilbaserade råvaror har dock bidragit till miljöproblem och drivit intresset för förnybara, biobaserade alternativ. Bland dessa erbjuder biobaserade drop-in-polymerer – kemiskt identiska med deras fossilbaserade motsvarigheter – en lovande lösning, eftersom de sömlöst integreras i befintliga produktions-, bearbetnings- och återvinningssystem.

Trots sin potential står biobaserade drop-in-material inför betydande utmaningar, inklusive höga produktionskostnader, begränsad tillgänglighet och pågående debatter om deras verkliga miljöfördelar. Nuvarande lösningar förlitar sig främst på socker- och kolhydratrika grödor som sockerrör, majs och vete, vilket ger upphov till oro över markanvändningskonkurrens med livsmedels- och foderproduktion. Som ett resultat av detta framstår användningen av sekundära råvaror från skogsbruket och jordbrukets biprodukter som en mer hållbar väg.

Den långa utvecklingscykeln för nya material – som ofta sträcker sig över 15–20 år – utgör ytterligare ett hinder för utbredd användning. Samtidigt drar väletablerad fossilbaserad plast nytta av ett sekel av teknisk förfining, optimerade leveranskedjor och en växande återvinningsinfrastruktur. Att övervinna dessa utmaningar kommer att kräva genombrott inom materialvetenskap, policystöd och ökad vilja bland industrier och konsumenter att investera i hållbara alternativ.

Även om biobaserad drop-in plast utgör ett viktigt steg mot att minska fossilberoendet, är de inte en fristående lösning på plastföroreningar och bredare miljöhänsyn. Istället måste de kompletteras med förbättrad återvinning, materialeffektivitet och ett mer strategiskt förhållningssätt till resursutnyttjande. Bioplastens framtid hänger på att hitta en balans mellan hållbarhet, ekonomisk bärkraft och skalbarhet inom det befintliga industriella landskapet.

Acronyms

PE	polyethylene
PP	polypropylene
LDPE	low density polyethylene
LLDPE	linear low-density polyethylene
MDPE	medium density polyethylene
HDPE	high density polyethylene
PET	polyethylene terephthalate
EVA	ethylene vinyl acetate
PHA	polyhydroxyalkanoate
PHB	polyhydroxybutyrate
PEF	polyethylene furanoate

1. Introduction

Plastics is the collective term for polymeric materials, where the diversity and specifications of plastic products and application are enormous based on the combination of polymer and additives. Because of their combination of unrivalled properties and low cost, plastics are the workhorse material of the modern economy, but throughout their life cycles they contribute to pollution and depletion of non-renewable natural resources.

Transferring from non-renewable raw material to renewable, biobased seems like a simple way forward to tackle this problem, and since several years back there are biobased drop-in solutions available on the market. However, despite the ambitious plans for rapid growth on the market these alternatives are struggling with capacity expansion, price levels, acceptance on the market and a growing concern regarding the real environmental benefits of the biobased solutions [1] [2].

In 2023 the global production of plastics reached 413.8 million metric tons [3]. A staggering amount, that has quadrupled over the last 30 years [4]. If the current growth of plastics production continues in the same pace globally, the sector will account for 20% of the total oil consumption by 2050 and 15% of the annual global carbon budget [5]. The biobased and bio-attributed alternatives constitute approximately 0.7% of this volume or 3.0 million metric tons in 2023 [6]. Despite an aggressive plan for expansion of the production capacity of the biobased polymers in the coming years their share of the overall production volume grows slowly.

Biobased raw materials are generally considered as materials derived from living organisms such as plants, animals, enzymes or microorganisms like bacteria, fungi or yeast. Currently the majority of the raw materials are collected from the agricultural landscape like corn, wheat, sugar cane etc. However, other sources of interest are forestry and marine materials as well as materials produced by microorganisms.

The utilisation of primary sources which, by extension, competes with food and feed to produce plastics constitutes a point of discussion which has contributed to the recommendations from EU to use secondary raw materials instead [7]. Secondary raw materials are collected from residual streams, not competing with food or feed, and will also not require extra resources like arable land, fertilizers or water.

The most abundant application of plastics is within the packaging industry which alone stands for approximately 40-45% of the global consumption closely followed by the building and construction industry with some 20%. The most common polymers in the packaging industry are polyethylene (PE), polypropylene (PP) and polyethylene terephthalate (PET). PE and PP are common materials also in the construction industry. The two polymers constitute as much as 45-50% of the world production of polymers together, while PET in its turn constitutes about 10%. Packages tend to have the shortest working life of all sectors and are considered the greatest source of plastic waste globally [8] [9].

1.1 Definition of Drop-in plastics

Bioplastics is a wide concept including not only biobased and bio-attributed plastic but also fossil-based biodegradable plastic, Figure 1. This explains why the utilization of the term bioplastics continues to contribute to the confusion not only amongst consumers but also within the industry. Despite this ambiguity, the industry has not yet agreed on clearer terms. To further complicate the distinction between the various fields in Figure 1, there is currently no minimum limit of bio-based content in the material for to be called biobased, although it must be stated how many percent that is bio-based. However, a content of at least 20% bio-based carbon is often required to receive different labels and certifications for biobased products.

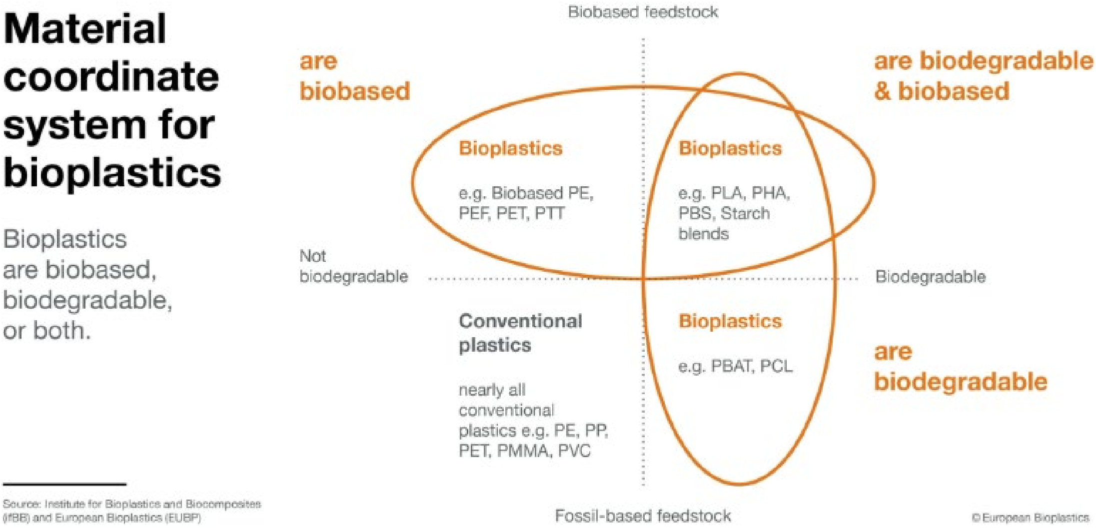

Figure 1. Material coordinate system for plastics materials, European Bioplastics[10]

Drop-in plastics are a subgroup within biobased bioplastics. The general definition of a drop-in solution is a bio-based material that has the same chemical structure and properties as its fossil-based counterpart.

Currently the drop-in materials encompass the polyolefins, with the general formula (CH2CHR)n, e.g. PE (with all its variants LDPE, LLDPE, MDPE, HDPE) and PP, which are available as 100% biobased.

PET, (C10H8O4)n, is also a drop-in material, however, it is not yet 100% biobased as it is only the monoethylene glycol-monomer, (CH2OH)2, that is biobased which renders the PET to be 30% biobased. A biobased ethylene vinyl acetate (EVA), (C2H4)n(C4H6O2)m, has also recently been introduced on the market. Compared with PE, PP and PET the volumes produced of EVA, both fossil and biobased, are low.

The benefits with drop-in solutions are that they are truly biobased replacements, hence the same chemistry as their petrochemical counterpart. This simplifies both processing of the material as well as the recycling of the material as it can be circulated in the same waste stream. Alternative biobased materials like polyhydroxyalkanoate (PHA) and polyhydroxybutyrate (PHB) can replace PE, PP or PET in certain applications having similar properties, or even better, but by not having the same chemistry they cannot be recycled in the same stream and are thereby not considered drop-in solutions.

Polyethylene furanoate (PEF) included in Figure 1, with the polyolefins, is a fully biobased alternative to PET, even though the chemical structure is different. Recently, the material has been approved to be recycled in the same stream as PET, hence the properties of the two polymers are so similar that no deterioration is expected upon mixing them. However, despite the promising properties of PEF the production capacity is still very limited.

Advantages with drop-in solutions can be summarized in a few points [11].

- Their use represents a small risk for end users, because their technical properties and manufacturing processes are already known by the value chain
- It is not necessary to adjust the plastic manufacturing machinery, reducing investment and generating lower switching costs for processors and end users, because it does not require new specialized complementary assets
- Lower recycling impact, because their materials are not depicted as contaminants in the recycling of conventional plastics

1.2 Global production capacity of Biopolymers

Despite all the efforts to grow the market share for biobased polymers the producers are struggling as the total capacity of polymers is growing fast and is estimated to reach 483.2 million tons by 2030. According to European bioplastics the global production capacity for biobased plastics will reach 5.7 million tons by 2029, which implies that the biobased volume will grow from todays 0.7% to approximately 1.2%, hence the share of the total market is growing slowly, Figure 2.

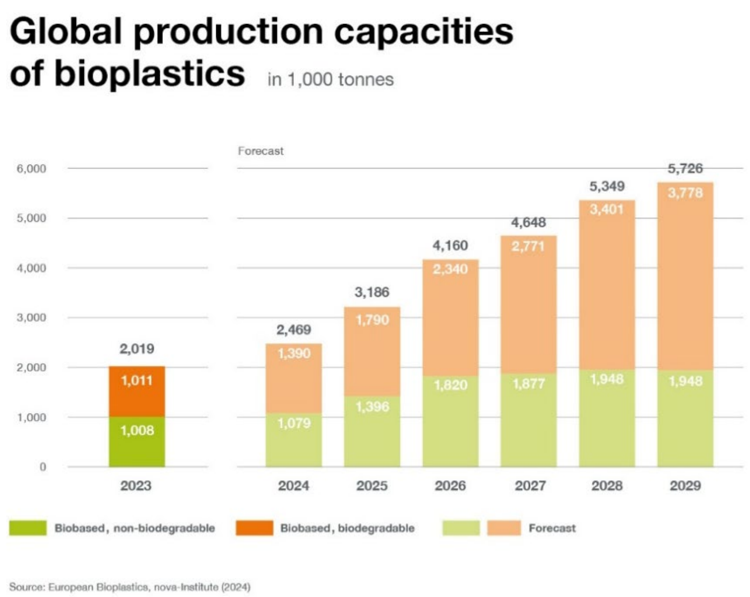

Figure 2. Global production capacity of biopolymers incl. fossil based biodegradable polymers, [12].

Both biobased PP and PET contributes with only minor volumes while PE has a more substantial amount of the total volume produced, Figure 3.

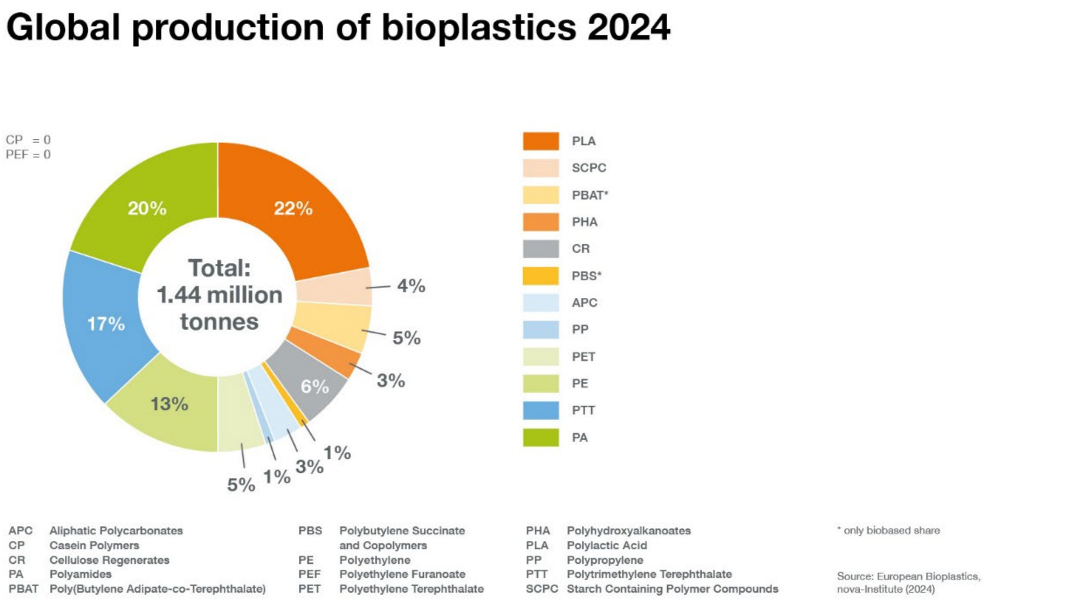

Figure 3. Percentage of the total volume for each biobased polymer [12].

It is estimated that the production capacity for biobased PP will grow substantially until 2029 going from approximately 1% of the capacity to 8.5%, Figure 4. At the same time the capacity of the drop-in alternatives will remain on a level of approximately 19% of the total capacity, as the major expansion is assumed to be related to the biodegradable alternatives like polylactic acid (PLA).

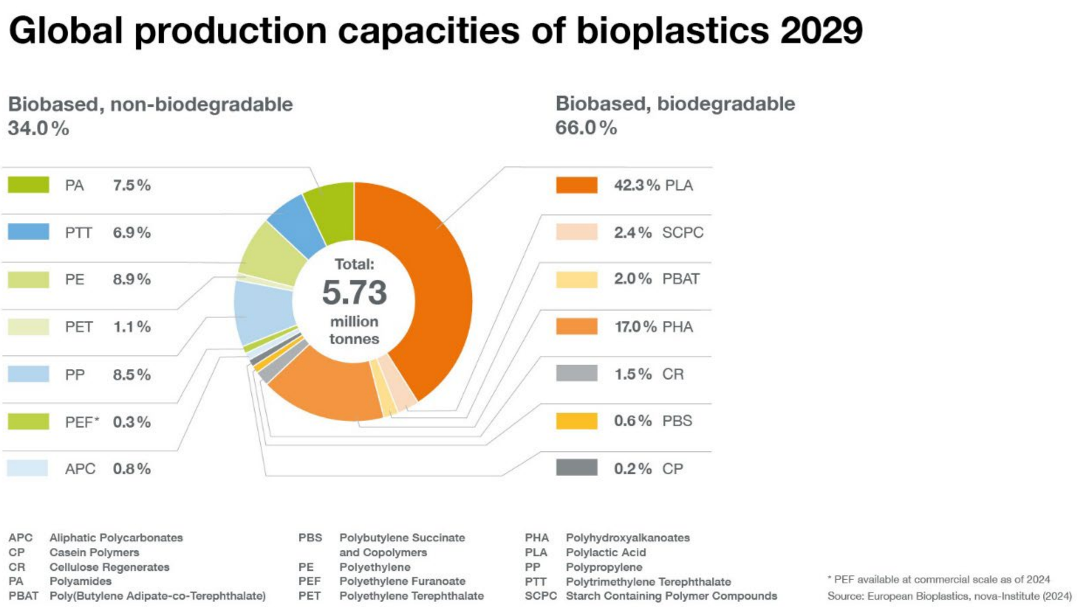

Figure 4. Percentage of the total volume for each biobased polymer, 2029 [12].

The market segment where the majority of the biobased polyolefin and PET volumes are applied is mainly the packaging industry, both flexible and rigid. In general packaging is the dominant application of plastics prior to construction and textile industry.

2. Manufacturing

2.1 Fossil-based Polyolefins

Polyolefins are among the most abundant polymers with a wide range of applications, with some 190 million tons production in 2022, of which PE constitutes approximately 110 million tons, and PP constitutes the remaining 80 million tons [13] [14].

The fossil production is generally based on a thermal cracking process of naphtha, to produce ethylene and propylene. Which, thereafter, are polymerised to form PE and PP, for example by a low-pressure catalytic process (Ziegler-Natta). The process is considered to be one of the most efficient with a high conversion and yield [15]. The process going from ethylene or propylene to its respective polymer is independent of what raw material that has been used, fossil or biobased.

Polyolefins are produced on all continents and both exported and imported based on available production capacity and consumption. Both North America and Middle East currently has an overproduction, while all other continents are net importers (Independent Commodity Intelligence Services, n.d.). China is known to have expansion plans to become self-sufficient on polyolefins, something that will have a great impact on the global product flow balance [16].

2.2 Biobased polyolefins suppliers

The supplier of biobased PE that perhaps is the most familiar due to an early introduction to the market is Braskem with their quality “I’m GreenTM” [17], utilizing sugarcane as the starting material. However, today there are several other suppliers providing biobased polyolefins to the market, utilizing the raw material that is the most economical in their respective geographical area for the production.

SABIC is marketing renewable polyolefins produced in their factory in Netherlands. The raw material used in the production is bio-naphtha, i.e. oil extracted from biomass sources like plant oil, animal residues or other organic matter. Bio-naphtha is mostly used for production of renewable diesel and aviation fuels. SABIC also utilises pyrolysis oil for the production, oil which is created from chemical recycling of low-quality mixed plastic waste.

Other suppliers that provide bio-based polyolefins to the market are for example LyondellBasell that have a joint effort with Neste resulting in Circulen and Circulen Plus, two mass balanced qualities, i.e. only partly biobased, and like SABICS material based on bio-naphtha. Then there is Total and Trioplast that uses bio-naphtha for production of TrioGreen a mass balanced quality of PE. DOW Chemicals has chosen a wood-based bio-naphtha, from UPM Biofuels, BioVerno, in their production of biobased PE. DOW has a partnership with Fuenix Ecogy for the supply of pyrolysis oil based on plastic waste for their production. Ineos has signed a long-term contract with UPM Biofuels, BioVerno, for their production of bio-attributed, i.e. mass balanced, polyolefins. Borealis also has a collaboration with Neste producing biobased polypropylene at an industrial scale in Belgium [18].

There are most likely additional suppliers, then what is mentioned here, already providing bio-based polyolefins on the market or investigating the potentials to join in.

2.3 Fossil-based polyethylene terephthalate

PET is alongside the polyolefins among the most common polymers utilized in food packages, especially bottles for beverages, and as textile fibres in clothes, home décor, furniture and so forth. In 2022 the global market volume reached almost 26 million tons [19].

PET consists of two building blocks, monethylene glycol and terephthalic acid, of which the glycol can be biobased and thus make a PET which is 30% biobased. The acid on the other hand is still fossil-based, however research work is ongoing as to produce the acid from renewable lignocellulosic biomass [20].

3. Renewable value chains for polyolefin production

The major fraction of olefins are produced by cracking of naphta from petroleum and natural gas feedstock. However, this chapter will focus on renewable feedstocks for olefin and polyolefin production, production processes and their technical and economic maturity as well as emerging technologies for producing olefins.

Olefins, the plattform molecules for producing polyolefins, as well as other important base chemicals, can be obtained through different routes, illustrated in Figure 5.

The feedstock used for these different routes may vary and include bio-waste, sugars, starch, bio-oils, lignocellulosic materials etc. The three more promising routes are described below [21]:

I. Dehydration of ethanol obtained from the fermentation of sugar, starch or cellulose, (ethanol-to-ethylene route),
II. Dehydration of methanol via gasification to synthesis gas (methanol-to-olefins, MTO reaction), and
III. Cracking of hydrotreated vegetable/bio oils

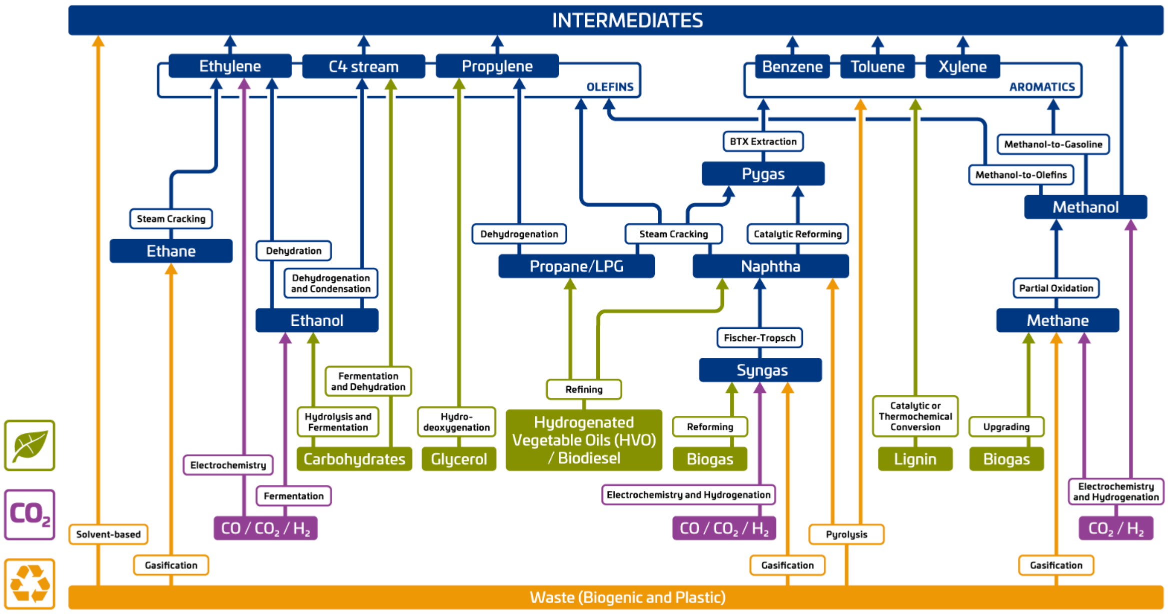

Figure 5. Routes for production of biobased olefins, Nova Institute, [22].

3.1 Ethanol-to-ethylene

Ethanol may be derived from fermentation of sugars and starch, lignocellulosic materials and waste biomass. Where the hydrolysis of lignocellulosic material is more difficult, compared to sugar/starch, due to the recalcitrance structure of lignin [23].

The ethanol-to-ethylene is an established industrial process, used by Braskem, Chematur, British Petroleum (BP), Axens, Total etc. [23]. Furthermore, as of 2020, Braskem produced 200 000 tonnes of bio-PE from sugarcane dervied ethanol [21].

However, a tecnoeconomic analysis by Mohsenzadeh et al. [23] stated that the production of bio-based plastics from the ethanol-to-ethylene process had a negative profit margin. Mainly due to the price of raw materials and products, compared to ethylene produced from naphta cracking, and would therefore require a premium price on the produced plastics. Similar conclusion regarding a premium price for biobased polymers was made by the Nova Insitute as early as 2013 [24].

3.2 Methanol-to-Olefins (MTO)

The methanol-to-olefin (MTO) process was first proposed by Mobile Corporation (ExxonMobil) in the late 70’s [25]. The advantages of the MTO process are the high selectivity and its complete methanol conversion [26].

In 2009, Total Petrochemicals built a MTO demonstration unit in Feluy, Belgium for producing ethylene and propylene from methanol. Recently the AP Möller company declared that they would launch a PE/PP plant, Vineo, in 2028 based on the MTO process. The feedstock will be green methanol, utilising renewable electricity, from a factory in Antwerp, Belgium [27].

Disadvantages with the MTO process is that the reaction stages (mechanisms) are not yet fully known and that the process require frequent catalyst generation due to the short-term stability (a few hours). However, progress on the long-term stability of catalysts is being made, for example the SAPO-34 catalyst that can exceed 450 reaction-generation cycles [26].

Furthermore, the price for the bio-olefin from the MTO process is high and a techno-economical calculation performed at VTT, Finland suggested a need for a premium price at 100 €/tonne bio-olefin to make the gasification/MTO route economically viable [28]. Furthermore, the report *From green forest to green commodity chemicals* [29] also showed that the biobased routes to produce polyolefins were less attractive than production from fossil resources due to economic reasons.

3.3 Cracking of hydrotreated bio-oils

Bio-oils such as vegetable oils and animal fats could be sourced from edible and/or non-edible biomass. Due to the higher oxygen content,10-40% [30], in bio-oils compared to crude oil, the direct feed of bio-oils to steam or catalytic cracking is problematic, due to the low miscibility in the hydrocarbon-containing feed. Therefore, bio-oils need to be upgraded before introduced into the same feed. For example, through catalytic hydrodeoxygenation (HDO) [30] a high-pressure process where oxygen is removed from the bio-oil through hydrogen treatment in the presence of a catalyst.

The advantage of using bio-oils as feedstock for polyolefins is the possibility to use existing processing infrastructure, such as cracker-plants [21]. However, vegetable oils are more expensive than sugar and starch, which increases the cost. Additionally, the hydrogenation step, utilizing hydrogen, would have to use green hydrogen for sustainability, and the feedstock used should not compete with the food value chain or lead to deforestation.

3.4 Pyrolysis and CO/CO_2 conversion

According to, Wang. Z, et.al [31] the challenge in producing bio-polyolefins are related to low yields and high costs. Further it is questioned to utilise arable land or crops aimed for food or feed for the production of materials, hence the search for alternative sources like secondary streams should be prioritised.

3.4.1 Biomass and Plastic-waste Pyrolysis

Pyrolysis, i.e., thermal degradation without oxygen, could allow conversion of bio-waste and even waste-plastics into light olefins [26]. As mentioned before, bio-wastes contain more oxygen than the fossil derived fuels which increases the processing steps towards olefins. Additionally, pyrolysis is more suitable for feedstocks with a low moisture content, due to the high energy demand associated with drying of wet feedstocks [32].

The advantages of pyrolysis to olefins are abundant and cheap feedstock, compared to fossil fuels. Hence, exploiting the possibility of using biowaste for olefin production, as an alternative to incineration, could be interesting from an environmental point of view [26][26]. However, to date, this technique is not mature enough for industrial processes.

There are commercial pyrolysis plants existing producing volumes for various applications. The pyrolysis oil from biomass is mostly used for fuel production. The challenge looking at plastic waste is the competition with mechanical recycling of the polyolefins as the most sought-after source, to achieve a high-quality oil from the process, are the polyolefins. With further development of the technology, so that mixed streams most probably consisting of a mixture of various plastic waste and biomass, can be utilized, the advantages with the pyrolysis process will become more evident.

3.4.2 CO and CO_2 conversion to Olefins

In the past decades, there has been a growing interest in CO and CO_2 conversion to olefins through Fisher-Tropsch synthesis or methanol mediated direct hydrogenation of CO and CO_2. Similar to the cracking of bio-oils (described in section 3.3), the hydrogen used in the hydrogenation step would have to be produced using renewable energy to ensure sustainability of this process.

However, commercialization is challenging due to the high capital costs, low efficiency, and low reliability of complicated process sequences [33]. Therefore, the utilization of CO_2/CO as a feedstock for producing olefins is currently limited to laboratory-scale.

4. Available Biomass

Biomass is a scarce resource and must be used wisely for applications with the highest economic and societal value in the transition to a net-zero economy. By looking into the future scenarios for utilisation of biomass for energy and materials there is a risk that there is an over-reliance on available biomass.

In EU it is considered that the available biomass corresponds to 11-13 EJ[1] [34]. This is to be sufficient for all possible applications in the transformation to a net-zero emission economy. Summing up the need of biomass to meet the future scenarios for energy, materials, chemical and so forth shows that there is a gap between expected use and available biomass of 40-70%, Figure 6.

[1] exajoule, 1EJ=1x10^{18}

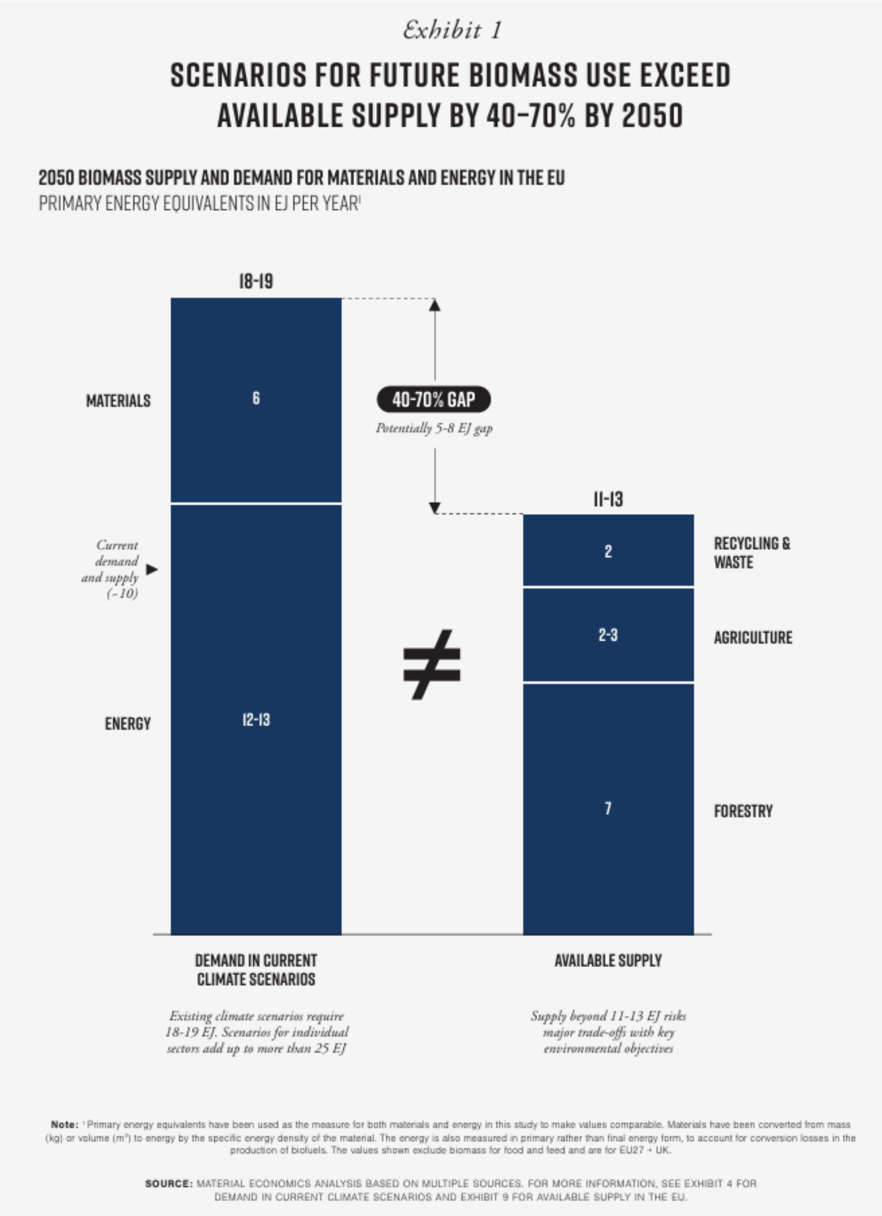

Figure 6. Scenarios for future biomass [34].

The different applications compete when it comes to access to the biomass. However, according to the EU communication[35] production of materials from biomass should overrule application for energy production. In parallel there is a transition towards an electrification and streamlining of both industrial processes and transportation, which will impact the need of biomass för energy production.

It is of utmost importance that the extraction of biomass is within a framework of a sound and sustainable growth of new biomass. There is a concern that with an increased outtake of biomass the delicate balance in nature might be disturbed with unknown consequences. In Scandinavia most of the biomass, approximately 70%, comes from forestry and is considered an abundant source in the north that we would like to utilise more effectively. However, the suggested update of the LULUCF-regulation [35] requesting that Sweden increase its uptake of CO_2, by letting the forest remain untouched, may on the other hand limit future plans of an increased outtake of biomass from the forest.

The available biomass in Sweden is estimated to 132TWh/y today with an additional conservative amount of 40TWh/year based on estimations of more efficient use of felled forest, use of straw and replanting of fallow land with, for example, grassland or energy forest, [36]. Updated numbers [37] indicates that by 2050 there could even be an additional 32TWh/y from the forest, 27TWh/y from agriculture and 1TWh/y from aquatic biomass, in total approximately 60 TWh/y.

4.1 Feedstock for Biobased Polymers

The feedstock for biobased polymers is biomass. The amount currently used for production of polymers is estimated to 0.028% of the global production of biomass, Figure 7. Which corresponds to 0.007% of the arable land, indicating that the opinion that there is a conflict with food and feed is perhaps exaggerated.

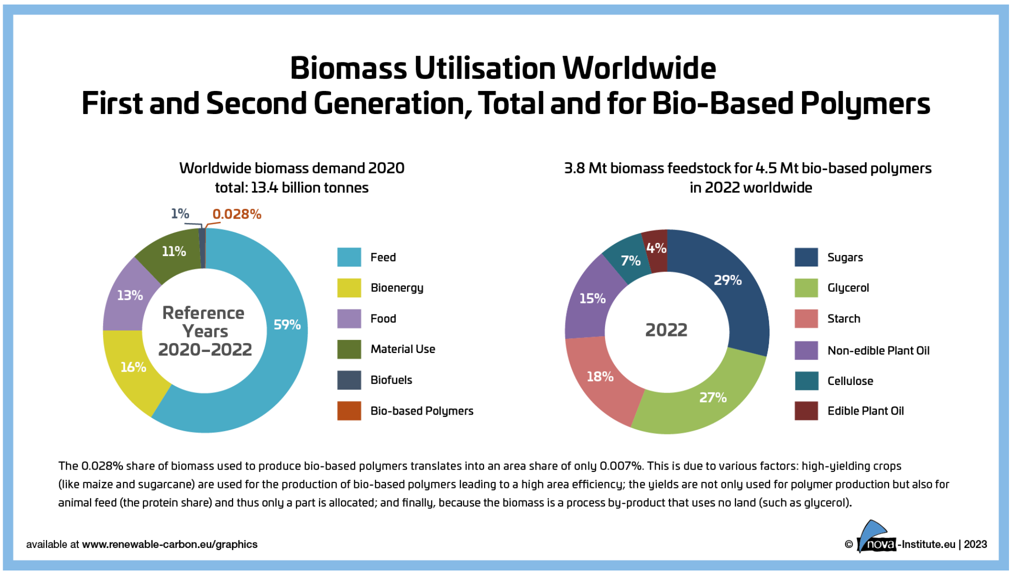

Figure 7. Biomass utilisation [38].

The most common raw materials used are either sugars, glycerol or starch, Figure 7. The majority comes from so called primary sources, or materials that has their primary value beeing either food or feed. However, the efficancy of different crops producing the necessary sugar or starch varies which strongly affects the need for the amount of crop needed, impact on land use management and water consumption, Figur 8. This makes it challenging validating which crop is the most suitable as rawmaterial.

Additionally, there are several other factors that also needs to be taken into account, like the conclusion from a study conducted [1] that none of the bio-based plastics are truly sustainable due to health and safety reasons like GMO crops, utilisation of pesticides, etc. Or as pointed out by OECD [39] where the sustainability of biobased feedstock for plastics is summarised as:

- The benefits of using this feedstock, demonstrated through life-cycle assessment (LCA), outweigh the cost of externalities, such as water consumption, and competition with food production or social or ecological land use.
- The availability and continuity of availability of the supply of the feedstock enables its use.

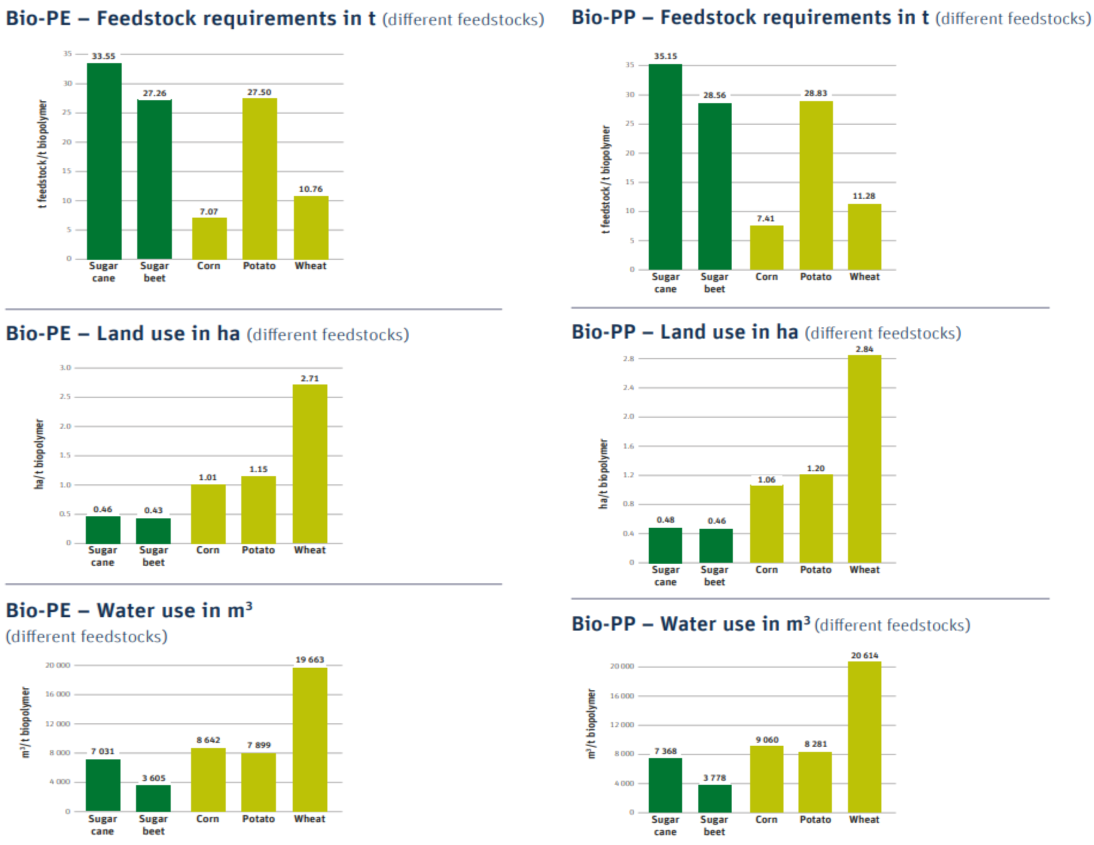

Figure 8. Feedstock requirement (Dark green-sugar, light green-starch) [40]

Despite the fact that there is very little amount of the biomass being used for production of polymers, EU has in its policy framwork on biobased, biodegradable and compostable plastics [35] stated that:

> *Utilizing primary sources for the production of plastics can have a detrimental impact on the environment, therefore secundary sources such as organic waste and by-product feeds are preferred sources for production of plastics and when primary sources are still being used it is vital to ensure that they are environmentaly sustainable.*

4.1.1 Lignocellulose

The most abundant source of biomass in the world is lignocellulose which makes it one of the most preferred bases for the future biobased industry providing materials like plastics and chemicals. In parallel there is the competition with the production of fuel, energy and heat that also heavily depends on biomass for their transition to a more sustainable operation.

Considering cellulose, the main source is naturally hard- and softwood but agricultural residues do also contain a considerable amount of lignocellulose [41]. Biomass that contains high levels of carbon is a favorable source for thermochemical processes like pyrolysis and gasification whose major products are the pyrolysis bio-oil, syngas, ethanol and methanol respectively.

There is an excess of agricultural residues especially in France, Germany and Romania, while there are only small amounts in the northern countries. Forestry residues, on the other hand, are high in Finland, Sweden and Austria [41]. The availability of lignocellulosic material in Sweden is currently 132 TWh/y [36].

4.1.2 Carbohydrates, Starch, Sugars

Agricultural residues are also rich in starch and sugar. Carbohydrates are important building-blocks in both food and feed. The proportion of the economic part, edible, and the residual part of crops are approximately 50/50. Most of the carbohydrates, starch and sugars are concentrated in the edible part of the plant, and there are crops such as wheat, corn and sugar beets grown solely for production of alcohols mainly aimed for the fuel industry. A shift away from fuel production could possibly occur if there is an increased focus on production of materials or chemicals.

Cellulose, which is the more dominant part in the residual part of the crops, can also be treated by fermentation or hydrolysis to provide sugars that can be used for production of alcohols.

The availability of straw as a residual stream in Sweden was in a report from 2016 [42], estimated to 3.6 TWh/y, which has been updated with numbers for additional supply potential until 2030 with 3 TWh/y [37].

4.1.3 Biogas

Production of biogas is mainly related to anaerobic digestion of sewage sludge, household waste, residuals from food production or manure. There is an increased interest in Sweden for both small- and large-scale biogas plants. Small plants are typically used for direct energy production making farms self-sufficient, while larger installations are used for production of biogas either as an energy source or as a raw material for the industry.

The domestic production in Sweden, 2023, was 2.3 TWh in the same year the consumption of biogas was 4.1 TWh [43].

4.1.4 Oils

Oil rich rapeseed together with tall-oil and waste from slaughter is used for fuel production and food. These oils can also be refined producing propane which can be turned into polypropylene. This is done in commercially today as mentioned in 2.2.

4.1.5 Aquatic sources, Algae

Algae are divided into macro- and microalgae, macro are the seaweeds while micro are photosynthetic organism. There is a potential using especially macroalgae as a bio-based feedstock for the industry especially for production of biogas in the future. Currently there are no major attempts to operate commercial farming in Sweden, however interest is growing and there are some small actors like Nordic Seafarm [44] and Kobb [45] supplying to the market.

Microalgae on the other hand are rich in oils and are thus claimed to be interesting as feedstock for production of fuel. However, this is still only in very early stages and only minor experiments have been performed [42].

The availability in 2050 is estimated to be 1 TWh/y [37].

4.1.6 Carbon capture and utilisation

Carbon capture and utilisation, turning the captured carbon dioxide into platform chemicals like methanol by reacting with hydrogen offers novel solutions to utilise carbon dioxide as a raw material, which helps to replace fossil fuels and chemicals and even produce entirely new products. Liquid Wind [46] for example are producing methanol as fuel for shipping.

4.1.7 Application areas

The interest to replace fossil feedstock with bio-based is valid for most of the chemical industry or related businesses. There are numerous applications that are requesting a share of the bio-based feedstock, where the majority has been and still is used for production of fuels, Figure 9 [47]. The implication or consequence is that the willingness to pay for the final product controls the flow of incoming raw materials.

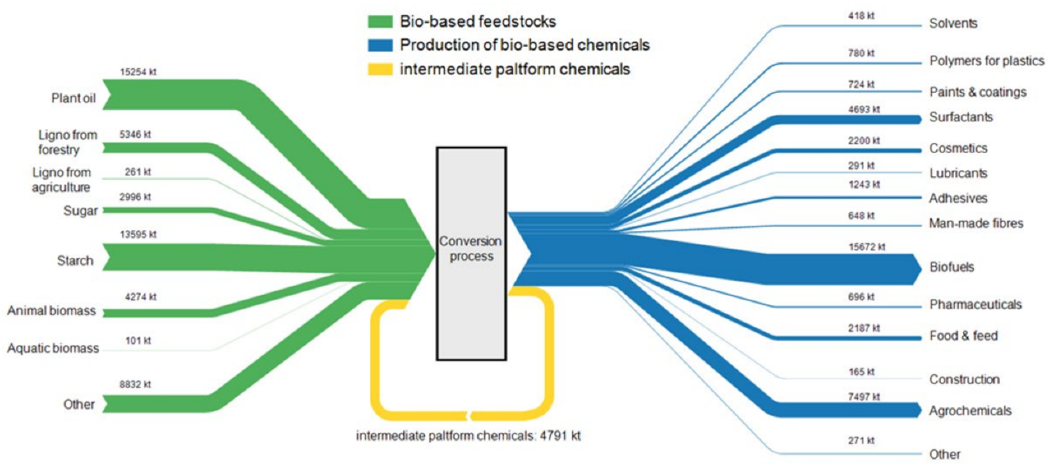

Figure 9. Use of biological resources for production of bio-based chemicals in the EU in 2018, [47].

4.2 Secondary sources as feedstock

Secondary sources like underutilised side- or residuals streams are clearly an option to be further evaluated as sustainable alternative raw materials. Not only may they be less costly but by utilising them as raw materials instead of for energy production, which is often the case, they can bring new values and businesses to the provider.

The valuable side- or residual streams are the once that contains cellulose, starch or sugars at a level that makes it economically viable to extract, they are the potential sources for future raw materials.

5. LCA and Financials

It is easy to assume that biobased alternatives are without doubt more sustainable than their fossil-based analogue. However, in many studies performed it becomes clear that the complexity of the LCA-methodologies and how decision are made will influence the outcome regarding the seven impact categories, i.e. energy use, ecotoxicity, acidification, eutrophication, climate change, particulate matter formation and ozone depletion, determining the borders and values leads to ambiguous results [48].

There are still many unknown parameters and trade-offs that needs to be studied further to fully understand the pros and cons of biobased plastics [49] [50] . In the end, it currently seems impossible to conclusively declare any polymer as having the least environmental impact, or that the use of renewable sources inherently implies sustainability [8].

One of the biggest hurdles for the expansion of biobased polymers is the price that is generally higher than for the fossil-based equivalent. How the market for the bio-based materials will evolve depends strongly on the prices of conventional plastics, hence, the price of crude-oil. Further other factors like technological progress, economy of scale and the cost of the bio-based raw materials will in its turn influence the price of the bio-based material [51]. In addition, there are various economic instruments and regulations that can be exploited by politicians. The political arena is however volatile and not always providing the long-term stability required to ensure the industry that investments made for the transition to more sustainable alternatives will be profitable over time.

6. Regulations and other political instruments

There are numerous regulations that have an impact on the utilization of polymers in the future, Figure 10. These regulations will impact all polymers, both fossil and bio-based, but some have more impact on the bio-based materials like the Bioeconomy strategi and the Green Deal with all its underlying regulations. At the same time, these regulations focus more on recirculation of materials than on producing and using new virgin materials, regardless of the raw material used, which speaks for the drop-in solutions.

Political instruments, like policies supporting sustainable alternatives over fossil-based can be used to support the progress of the transition to more bio-based material, [51]. Further, taxes specifically imposed on fossil-based products could lead to an increase in the price of conventional plastics, potentially leading to reduced prices for bioplastics. Subsidies could be another alternative supporting decreasing the price-gap.

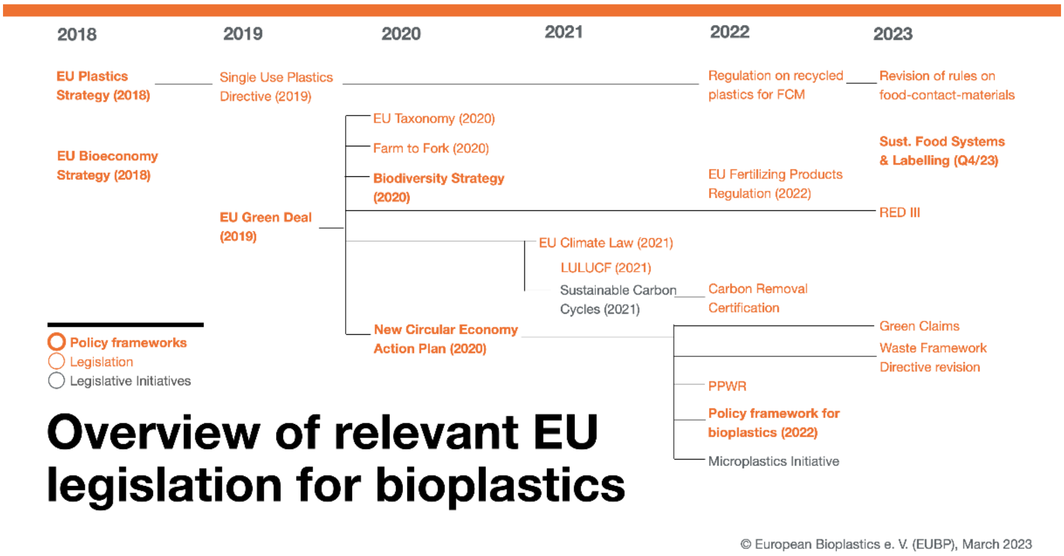

Figure 10. Relevant EU policies [52].

7. End-of-life

The production, utilisation and disposal of plastics is estimated to represent 2% of the global CO_2-output, with an uncertainty linked to undocumented open burning of plastics that can more than double the CO_2 emissions [53] [54]. By replacing the fossil raw material with biobased, recycle all plastics, switch existing process to renewable energy supply and reduce consumption of plastics by 50%, it is calculated that CO_2-emissions can be reduced by 93% [55].

7.1 Recycling

Efficient and economically viable recycling often requires large volumes. Thus, the vast quantities produced of the polyolefins would enable an efficient recycling system. However, the recycling rate of plastics is still very low, approximately 9% globally, 12% incinerated and 79% put on landfills, hence the lion part of the volume is lost from the system.

Polyolefin materials have two advantages that makes them valuable for recycling. Firstly, their inherent thermoplastic properties supporting mechanical recycling, an energy efficient process circulating the material into new products. The challenge with mechanical recycling is to keep the material on a high technical level.

Secondly, the material does not contain heteroatoms that hinders chemical recycling, thus the outcome from a chemical recycling process will constitute a valuable raw material for the chemical industry. To become a true alternative to crude oil the volumes need to increase substantially but also the view of waste versus raw material needs to be changed.

7.2 Biodegradability

Drop-in solutions are inherently non-biodegradable as the aim with the material is to resemble and replace current non-degradable fossil-based materials. From a value perspective it can be argued that it is preferable to have non-degradable materials as they can be recycled, hence, the carbon atoms will be kept in a continuous circle instead of turned into CO_2 from degradation.

7.3 Incineration

The advantage with biobased materials when incinerated for energy production, which should be used only when recycling is no longer an option, is that the CO_2 formed is considered not net-contributing to the atmosphere, thus in an LCA assessment the impact will be far less than for fossil-based materials.

8. Conclusion

Success of bioplastics depends on breakthrough materials and technologies, as well as the ability to compete with well-established materials and production methods. Which have had more than a century of technology development, sophisticated production and conversion, complex yet established supply chains and market channels, as well as growing infrastructure for recycling.

The long lag time for new materials to realize returns is a major frustration among companies. In many cases, it can take 15-20 years for a new material to yield substantial revenue from the development of new markets and/or applications, and bioplastics are no exception. Therefore, firms producing or using current materials could be more interested in finding biobased routes to established plastics (drop-in) that fit in existing conversion and disposal infrastructure.

Biobased drop-in solutions represent an interesting and emerging industrial field due to their inherent ability to fully behave as their fossil-based counterparts. None the less there is an obvious risk that just by replacing todays fossil-based plastics with biobased alternatives will not be the single answer to reducing or fighting against plastic-related pollution, health issues, environmental challenges and so forth.

There are already drop-in solutions available on the market, but in limited quantities, and to a premium price. The main raw materials are crops rich in sugars or carbohydrates like sugarcane, sugar beet, corn, wheat and potatoes. With the increasing debate on the competition with food, feed and use of arable land secondary sources becomes more attractive.

The availability of biomass and how it should be utilised to make the greatest benefit in the transition to a more sustainable society is also a topic where discussions are ongoing. In general, we have to be more frugal with all our resources, as they might become the limiting factor for all industrial activities in the future. Reuse and recirculation are high on the agenda which makes the drop-in solutions even more interesting as they can be recirculated utilising todays established systems. Recirculated materials are also in focus as legal requirements on more sustainable solutions are emerging.

The premium price for the bio-based drop-in materials is the biggest obstacle preventing a faster market growth. The development of the price is also difficult to anticipate as it depends on several factors. The factors are not only controlled by the industry itself but also dependent on political instruments and last but not least the willingness-to-pay for a more sustainable solution.

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