Challenges and opportunities toward a sustainable bio-based chemical sector in Europe

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OVERVIEW

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Challenges and opportunities toward a sustainable bio-based chemical sector in Europe

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Abstract
The chemical sector is the fourth largest industry in the European Union (EU) and the second largest chemical producer globally. However, its global share in chemicals sales has declined from 25% two decades ago to around 14% now. The sector, which accounts for 22% of the EU industry's energy demands, faces significant challenges in mitigating climate change, reducing pollution and toxicity, and improving circularity. Biomass, a promising renewable feedstock, currently represents only 3% of the sector's feedstocks. This review explores the opportunities and challenges for a bio-based chemical sector in the EU, particularly plastics, to improve circularity and contribute to climate neutrality, reduction of pollution and toxicity. It provides an overview of current fossil-based feedstocks, production processes, country-specific trends, bio-based production, and sustainability initiatives. Exploring new feedstocks such as lignin, organic residues, and algae can increase biomass availability toward a circular bioeconomy. Integrating chemicals and plastics production into commercial pulp and power factories, biofuel plants, and the sustainable hydrogen economy could boost the sector. Hydrogen is crucial for reducing biomass's oxygen content. These can ultimately contribute to reduce climate change impacts. Designing novel chemicals and plastics to accommodate biomass's higher oxygen content, reduce toxicity, and enhance biodegradability is essential. However, plastic waste mismanagement cannot be solved by merely replacing fossil feedstocks with biomass. Sustainability initiatives can strengthen and develop a circular bio-based chemical sector, but better management of bio-based plastic waste and transparent labeling of bio-based

products are needed. This calls for collaborative efforts among citizens, academia, policymakers, and industry.

This article is categorized under:
Climate and Environment > Circular Economy
Climate and Environment > Net Zero Planning and Decarbonization
Emerging Technologies > Materials

KEYWORDS
bioeconomy, climate neutrality, plastic pollution, plastic toxicity

1 | INTRODUCTION

A transition to a low-carbon and circular economy is necessary to mitigate climate change, shifting from fossil to renewable feedstocks. In the European Union (EU), about 60 million tons (Mt) of carbon dioxide equivalent are emitted annually by the chemical sector, the third largest greenhouse gas (GHG) emitter in the EU, only behind the cement, and the iron and steel industries (EEA, 2022). However, mitigation of climate change is not the only challenge faced by the chemical sector. Around 25–30 Mt of plastic waste is generated annually in the EU, and merely 35% of it is recycled (PlasticsEurope, 2022). Roughly 80% of chemicals produced are hazardous to human health, and 28% are classified as a very toxic health hazard (EUROSTAT, 2023a). The sector's high consumption of fossil energy carriers, half as an energy source and half as a feedstock (EC, 2023a), coupled with its linearity and reliance on imported energy and raw materials (EC, 2020a; EC, 2023a), makes it vulnerable to price fluctuations and volatilities, as experienced during the COVID pandemic and the war in Ukraine (EC, 2022; EC, 2023a). Biomass is a promising renewable feedstock to replace conventional fossil-based feedstocks, potentially contributing to climate neutrality, to a circular bioeconomy, and to reduce pollution and toxicity. Recent research shows that bio-based plastics can on average emit less GHGs than fossil equivalents (Meys et al., 2021; Zheng & Suh, 2019). The cascading use of biomass adds value to waste and residues locally produced (Muscat et al., 2021; Sharma et al., 2021), circulating raw material (Stegmann et al., 2020), reducing dependence on feedstock imports (Spierling et al., 2018), and supporting rural development (Philippidis, M'barek, Urban-Boysen, & van Zeist, 2023). Bio-based chemicals can have the same structure and/or properties as their fossil counterparts but can also deliver new functionalities and services and can show lower toxicity (Ismagilova et al., 2023), improved biodegradability, and improved recyclability (Rosenboom et al., 2022; Xia et al., 2021).

Yet a large-scale deployment of bio-based chemicals in the EU faces important challenges. Bio-based resources are limited in availability and there is substantial competition for biomass resources across sectors, as the transition to a circular bioeconomy demands substantial quantities of biomass, but as of today only 3% of the EU chemical production is bio-based (PlasticsEurope, 2022). The sustainability of bio-based products is dependent on biomass availability, conversion processes, use phase and end-of-life (Ögmundarson et al., 2020). A robust benchmark with the commercial fossil counterparts is challenging, as many bio-based technologies are still in the early stages of development with low technology readiness levels (TRL) (Souza et al., 2023), and most assessments focus only on potential GHG mitigation (Ögmundarson et al., 2020; Rosenboom et al., 2022).

In this context, a critical assessment of biomass potentials to mitigate sustainability changes of the EU chemical sector is currently missing. This review therefore explores the opportunities and challenges of relying on biomass as a renewable feedstock for a large-scale production of chemicals in the EU, toward improved circularity, climate neutrality, and reduction of pollution and toxicity. A comprehensive overview of the EU chemical sector is provided, presenting the most utilized feedstocks and production processes, the geographical trends, the current bio-based production, and the existing sustainability initiatives. These sustainability initiatives are assessed by identifying the main challenges for a successful transition to a circular bio-based chemical sector. The analysis is divided into three main sections: overview of the chemical sector, challenges and opportunities for the bio-based chemical production in EU, and overall conclusions.

2 | OVERVIEW OF THE CHEMICAL SECTOR IN THE EU

2.1 | The strategic role of the EU chemical sector

The chemical sector plays a strategic role in the EU economy (EC, 2020a; EC, 2023a), having large potential to contribute to the EU Green Deal (EC, 2015) and the twin transition (i.e., green, and digital) of the industrial sector (CEFIC, 2022; EC, 2023a).

The chemical sector is the fourth largest industry in the EU, and the second largest chemical producer in the world, generating about €465 billion in sales in 2020 (Eurostat, 2023b). The EU sales are far behind China, the world's leading chemical producer, which achieved €1.547 billion in sales for the same period (CEFIC, 2022). The EU chemical sector has around 31,000 industrial sites (Eurostat, 2023b), and most of these companies (95%) are small and medium-sized enterprises. This sector employs around 5.5 million people, 25% directly and 75% indirectly, plus around 19 million jobs throughout the chemicals supply chain (EC, 2020a; EC, 2023a). Labor within the chemical sector demonstrates high productivity, standing 67% above the average for the manufacturing sector (EC, 2023a). The chemical industry is highly concentrated in Germany, France, Italy, Poland, and the Netherlands (Eurostat, 2023a) (Figure 1), and Germany leads the production, turnover, and employment (Figure 1a,c,d). The production value of chemicals in Germany is around €135 billion a year, representing 29% of the EU's production value of chemicals, the country's turnover of chemicals is €167 billion, or 32% of EU's share, and the number of persons employed in the chemical sector is 354,000 people. Italy leads the ranking of number of enterprises, with around 4000 chemical plants and 8000 plastic plants. The total EU and non-EU values are presented on Table S1.

2.2 | Production of chemicals and plastics in the EU

A large range of chemicals is produced in the EU, and we selected key platform chemicals that serve as building blocks for other chemicals and polymers production, for example, ethylene is used to produce polyethylene, polyvinyl chloride, ethylbenzene, among others. The 12 selected chemicals (Figure 2) totalize around 80 Mt of production annually in the EU. Hydrogen (21%), ethylene (18%), and propylene (15%) are the three largest produced chemicals in the EU, and are concentrated in Germany, which holds up to 35% of their production. For total EU and non-EU production values refer to Table S2.

The chemical sector comprises five primary subsectors (Figure 3a) (EC, 2016), with plastics standing out as a key industry. This subsector includes producers of plastic raw materials, plastic converters, plastic recyclers, and plastic & rubber machinery producers (PlasticsEurope, 2022). The application of plastic products in the EU is concentrated in the packaging (39.1%), building and construction (21.3%), and the automotive industry (8.6%) (Figure 3b) (PlasticsEurope, 2022). In 2021, the EU plastic production reached 57.2 Mt, representing 15% of global production, only behind production in China (32%) and the North American Free Trade Agreement (NAFTA) (18%). The top three most produced plastics are polyethylene (24%), followed by polypropylene (17%), and polyvinyl chloride (11%). The share of recycled plastics, although increasing, is extremely low and only reached 10% in 2021 (PlasticsEurope, 2022). Bio-based or bio-attributed plastics are still only 2.3% of produced plastics in the EU (Figure 3c) (PlasticsEurope, 2022). Germany leads the production of polyethylene (20%), and polyvinyl chloride (34%), while Belgium produces 21% of total polypropylene (Figure 3d). For total EU and non-EU production values refer to Table S3.

2.3 | Feedstocks and production processes

The EU chemical sector produces a large range of products and intermediates that derive from a set of common feedstocks and processes. Fossil feedstocks are currently utilized in most applications and naphtha, natural gas, and heavy fuel oil are the most used ones (OECD/IEA, 2018; PetrochemicalsEurope, 2023) (Table 1). Naphtha is the most common feedstock to produce ethylene, propylene, benzene, toluene and xylene, and natural gas to produce methanol, ammonia, and hydrogen (OECD/IEA, 2018). The processes with the largest consumption of feedstocks are the steam cracking process and the production of hydrogen, aromatics, ammonia/urea, and ethyl benzene (OECD/IEA, 2018).

In terms of energy consumption, around two terajoules (TJ) of energy were consumed in the chemical sector in 2020, which represented 22% of the total energy consumption of the whole EU industry (EC, 2022). Natural gas represents around 33% of the energy-carrier consumption for chemicals and chemical products, followed by electricity

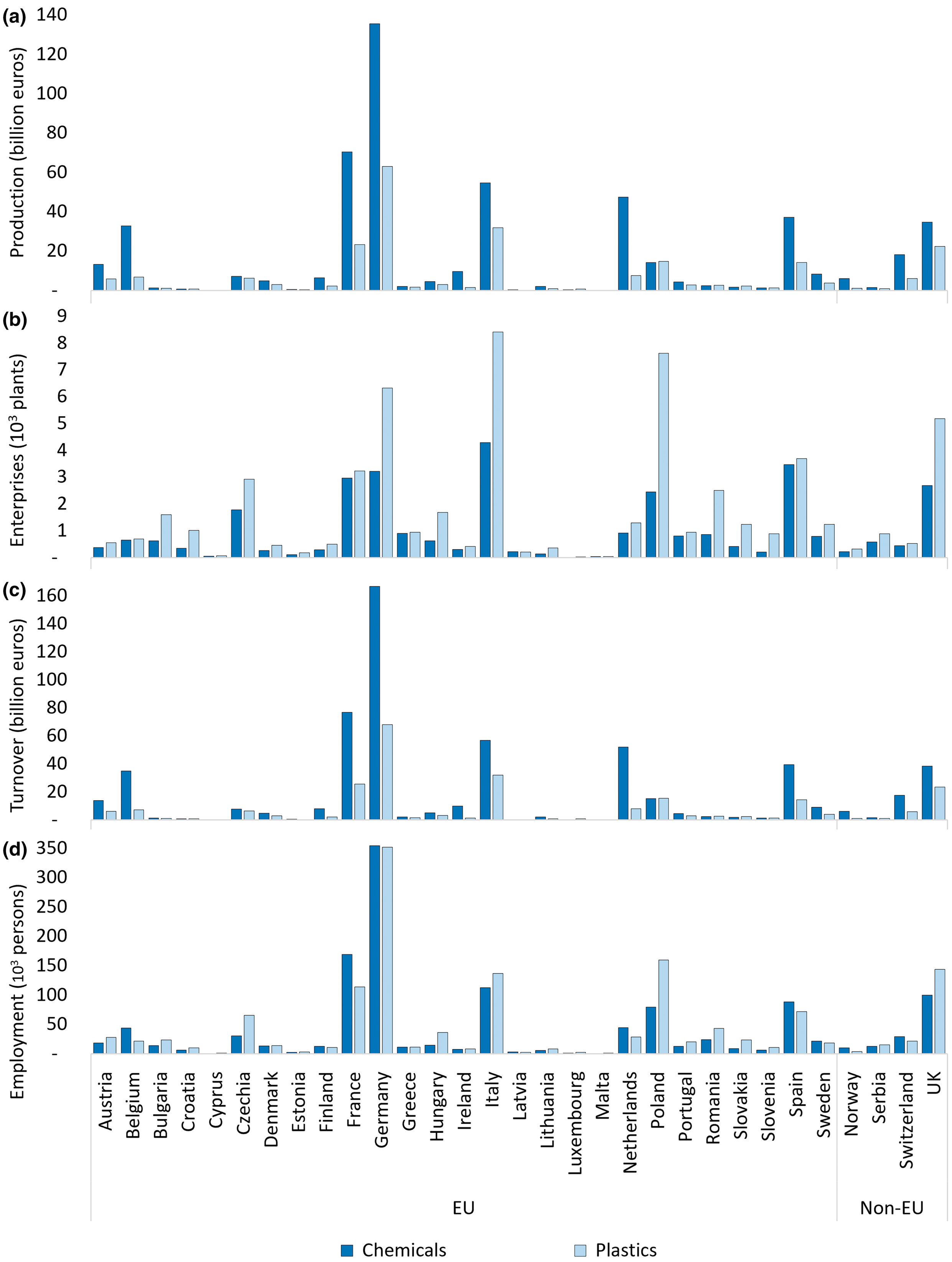

FIGURE 1 Chemicals sector in Europe: (a) production value, (b) number of enterprises, (c) turnover and (d) number of people employed, average from 2011 to 2020. *Source*: Eurostat (2023a).

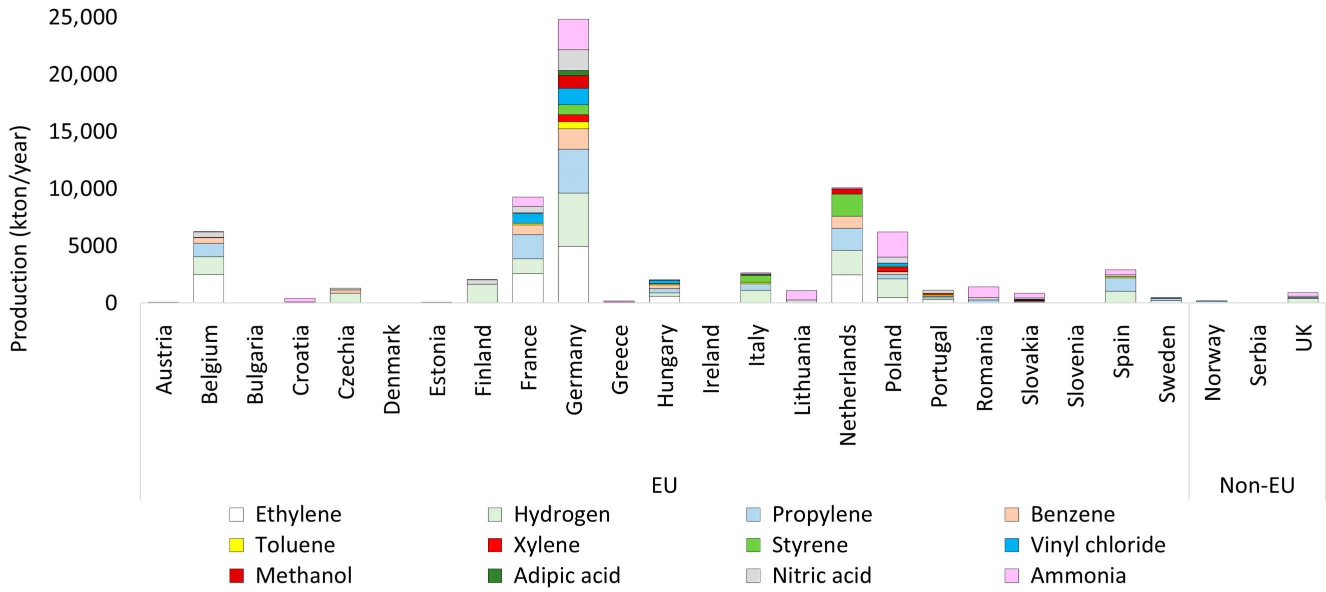

FIGURE 2 Production of chemicals in Europe, per country, average from 2011 to 2020. *Source*: Eurostat (2023c).

(26.1%), oil and petroleum products (19.4%), and heat (15.2%) (CEFIC, 2022; EC, 2022). The high energy costs are a hotspot for the sector, although energy consumption decreased by 21% since 1990, the energy costs in the EU are still higher than the ones from NAFTA and the Middle East, two large chemical producers that have access to relatively cheaper (fossil) feedstocks (CEFIC, 2022).

The sector's GHG emissions in the production phase of chemicals reduced by 72% in the last two decades (Figure 4) (EEA, 2022). The reductions are mostly attributed to abatement of fugitive emissions, that were mostly N_2O emissions (CEFIC, 2022), and to strong legislation to mitigate emissions (EC, 2016). In the EU, Romania, Italy, Germany, and France had achieved the largest GHG relative reductions, up to 82%, while Belgium and Lithuania reduced their sector emissions by less than 15%. The total European GHG emissions are presented on Table S4.To achieve climate change mitigation targets and reach net zero, the chemical sector still requires a significant effort to reduce the 60 Mt of GHG emissions (CEFIC, 2022; EC, 2023a), mainly in the ammonia, hydrogen/syngas, steam cracking, nitric acid, and chlorine production processes, which are the five largest GHG emitters (Boulamanti & Moya Rivera, 2017; EEA, 2022).

2.4 | Bio-based production

The combination of climate change mitigation targets, a rise in oil prices, and growing demand is contributing to a bio-based transition in the chemical sector (Jong et al., 2020). Bio-based chemicals and plastics are an opportunity to improve the sustainability of the EU chemical sector (Baldoni et al., 2021). However, less than 5 Mt of bio-based chemicals are produced in the EU, only 3% of the total chemical-based production (Table 2). Surfactants have the highest bio-based share (50%), followed by cosmetics and personal care (44%), but their production (3 Mt and 1.3 Mt, respectively) is considerably smaller than platform chemicals (60.8 Mt) and polymers production (57.2 Mt), for example, that currently have less than 2% of bio-based share in total production (PlasticsEurope, 2022; Spekreijse et al., 2019).

Around 1060 Mt of biomass (dry matter) are annually used in the EU, divided in 48% for food and feed purposes, 20% is unknown or lost, 19% for energy purposes, and 12% for biomaterials purposes (Gurría et al., 2022), including the chemical sector. Oily, sugary, and starchy crops are among the most common feedstocks to produce bio-based chemicals (Jong et al., 2020; Spekreijse et al., 2019). Due to competition for land resources, the attention is shifting from the use of these common crops to the valorization of lignocellulosic crops and residues, and of organic wastes to produce chemicals (Jong et al., 2020).

The most produced bio-based chemicals in the EU are lactic acid, succinic acid and furfuryl alcohol, they represent a share of 54%, 46% and 13% of the world's production, respectively (Baldoni et al., 2021). As for plastics, the current production can be divided in drop-in bio-based plastics, that provide the exact same structure and properties as the fossil counterparts, and in dedicated bio-based plastics, that provide different chemical and mechanical properties than the fossil

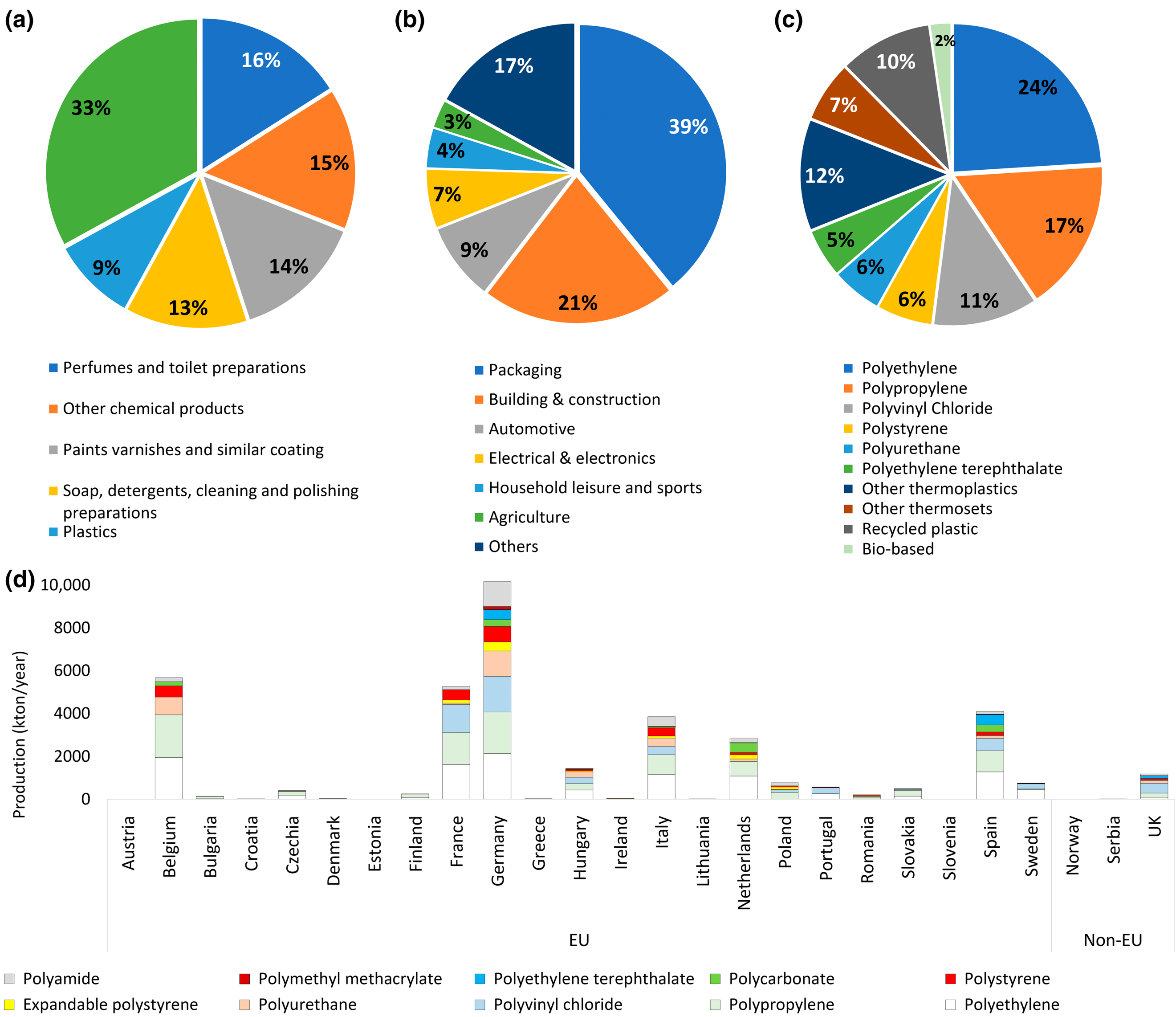

FIGURE 3 Subsectors of the chemical sector (a), plastic types (b), plastic applications (c), and plastic production per country (d), average from 2011 to 2020. *Source*: Eurostat (2023c), EC (2016), and PlasticsEurope (2022).

counterparts (Zheng & Suh, 2019). Drop-in bio-based plastics include bio-polyethylene and bio-polyethylene terephthalate; dedicated plastics include polylactic acid, polyhydroxyalkanoates and thermoplastic starch (Rosenboom et al., 2022).

The production of platform chemicals that can be polymerized into a range of bio-based plastics is projected to grow by 10% per year mostly due to increased demand for sustainable products and due to market regulations in the EU (Rosenboom et al., 2022). Germany, Italy, France, Spain, and the Netherlands have high estimated capacities to produce bio-based chemicals and plastics in the near future (Spekreijse et al., 2021). Germany leads the ranking with around 1.7 Mt per year of potential production capacity of bio-based chemicals, and 254 Mt per year of bio-based plastics (Spekreijse et al., 2021). These countries are also in the top ranking of fossil chemical production in the EU (Section 2.2) and are currently the largest producers of bio-based chemicals and plastics.

The bio-based chemical sector (i.e., chemicals, rubbers, and plastics) in the EU employs approximately 165,000 people, generates a turnover of €58 billion, and adds a value of around €15 billion annually (López et al., 2022). Germany and France contribute significantly to the EU's bio-based chemical sector, accounting for 26% and 14% of the employed persons (Figure 5a), 28% and 15% of the turnover (Figure 5b), and 28% and 16% of the added value (Figure 5c), respectively. However, when comparing the socioeconomic indicators of the bio-based chemical sector with the entire bioeconomy (which also includes bio-based textiles, wood products and furniture, paper, liquid biofuels, and bio-based electricity), bio-based chemicals contribute, on average, to just 1% of the bioeconomy in most of the EU countries

TABLE 1 Processes and feedstocks for chemicals production.

Feedstocks	Intermediate feedstock	Processes	Products
Naphtha and natural gas	–	Cracking	Ethylene
Naphtha and natural gas	–	Cracking	Propylene
Natural gas	Syngas	Steam reforming	Ammonia
Naphtha and pygas	–	Catalytic reforming	Benzene
Naphtha and pygas	–	Catalytic reforming	Toluene
Naphtha and pygas	–	Catalytic reforming	Xylene
Natural gas	Syngas	Steam reforming	Methanol
Naphtha	Cyclohexane	Oxidation	Adipic acid
Natural gas	Ammonia	Oxidation	Nitric acid
Natural gas	Ammonia	Urea synthesis	Urea
Natural gas	–	Solvay	Soda Ash

Source: Summary based on original data from Boulamanti and Moya Rivera (2017), PlasticsEurope (2022), and OECD/IEA (2018).

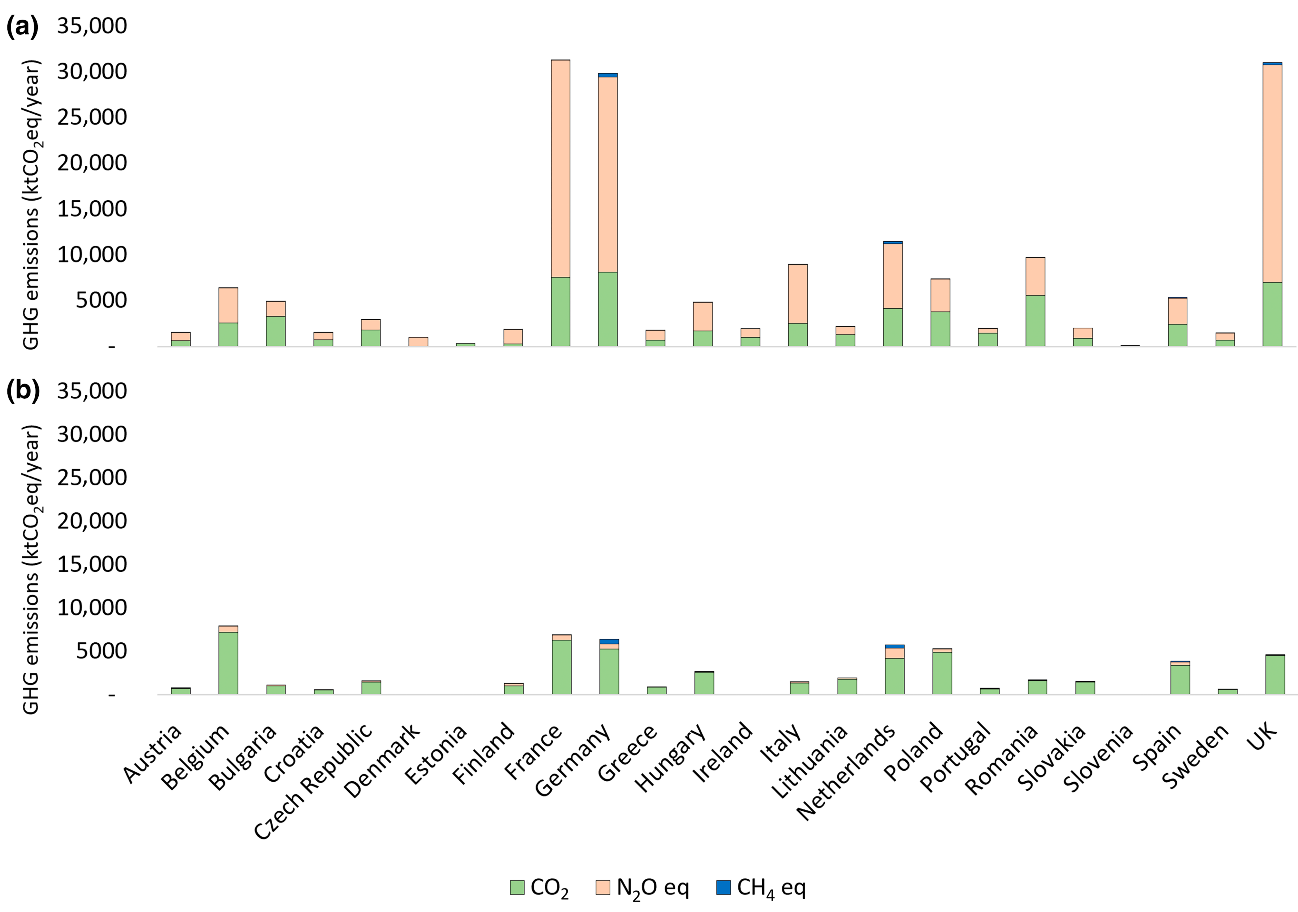

FIGURE 4 GHG emissions, by type of gas, in the European chemical sector in (a) 1990 and (b) 2020. *Source*: Summary based on original data from EEA (2022).

(Figure 5d). The highest contribution comes from Denmark, where the added value of bio-based chemicals represents 6% of the country's bioeconomy's added value. Absolute values for persons employed, turnover, and added value, as well as total EU values, can be found in Table S5.

The assessment of social impacts in the bio-based sector at the EU level is a recent development. The EU Bioeconomy Monitoring System (Knowledge Centre for Bioeconomy, 2024) provides a set of sustainability indicators and has recently

TABLE 2 Overview of the bio-based chemical sector in the EU.

Product category	Total production (Mt)	Bio-based production (Mt)	Bio-based share (%)	Most used feedstocks[a]
Platform chemicals	60.8	0.2	0.3	Sugar/starch and vegetable oils
Solvents	5.0	0.1	1.5	Wood and sugar/starch
Polymers for plastics	57.2	1.3*	2.3*	Sugar/starch
Paints, coatings, inks and dyes	10.3	1.0	12.5	Vegetable oils
Surfactants	3.0	1.5	50	Vegetable oils and sugar/starch
Cosmetics and personal care	1.3	0.6	44	Vegetable oil, sugar/starch, others
Adhesives	2.7	0.2	9	Wood and others
Lubricants	6.8	0.2	3.5	Vegetable oil
Plasticizers	1.3	0.1	9	Sugar/starch and vegetable oil
Man-made fibers	4.5	0.6	13	Wood and vegetable oil
Total	155.6	4.7	3	Vegetable oil
References	Spekreijse et al. (2019)	Spekreijse et al. (2019) *PlasticsEurope (2022)	Spekreijse et al. (2019) *PlasticsEurope (2022)	Spekreijse et al. (2019)

[a]Most used feedstocks are presented first.
Source: Summary based on original data from Spekreijse et al. (2019) and PlasticsEurope (2022).

undergone updates, expanding socioeconomic information disaggregated by country and bio-based sector in the EU (European Commission, 2023; Patani et al., 2024). However, it still lacks disaggregation by type of bio-based chemical and plastic product. The BioMonitor project is improving data transparency in the EU bioeconomy (Philippidis, M'barek, & van Zeist, 2023) and has created an online platform for easy access to bioeconomy socioeconomic indicators (López et al., 2022). The BioMat project (Sturm et al., 2023) is working to provide disaggregated information on feedstock demand and the historical development of bio-based products at the EU level. These two projects are crucial for improving the socioeconomic assessment of the bio-based chemical sector (Baldoni et al., 2021; Sturm et al., 2023).

2.5 | Sustainability initiatives

The EU has a set of sustainability strategies, plans, directives, guidelines, and so forth in place that directly or indirectly affect the chemical sector and will be explored below. For simplification purposes, here we refer to them as "sustainability initiatives."

The European Green Deal sets to reduce the impacts of all industrial sectors in the EU. The chemical industry is particularly affected (a) by the climate neutrality targets to be met by 2050; (b) by the use of renewable energy and increase in energy efficiency; (c) by the impacts on the environment (i.e., reducing plastic waste, litter and microplastics and impacts on biodiversity) and health (i.e., chemicals toxicity); (d) and by the need of improved circularity, including better waste management for higher material recycling (EC, 2023a). However, even before the Green Deal, several legislations had already been implemented in the EU chemical sector to address global warming, industrial emissions in general, air and water quality, to regulate waste generation and disposal, and to prevent industrial risks and accidents (EC, 2016). The "Regulation on Registration, Evaluation, Authorisation and Restriction of Chemicals" (REACH) and the "Regulation on the Classification, Labelling and Packaging of hazardous substances" (CLP) address the safety of toys, cosmetics, biocides, plant protection products, food, carcinogens in the workplace, and legislation on environmental protection (EC, 2020a). The sector also relies on directives regarding integrated pollution prevention and control (IPPC) (EC, 2010) that guides the implementation of new industrial

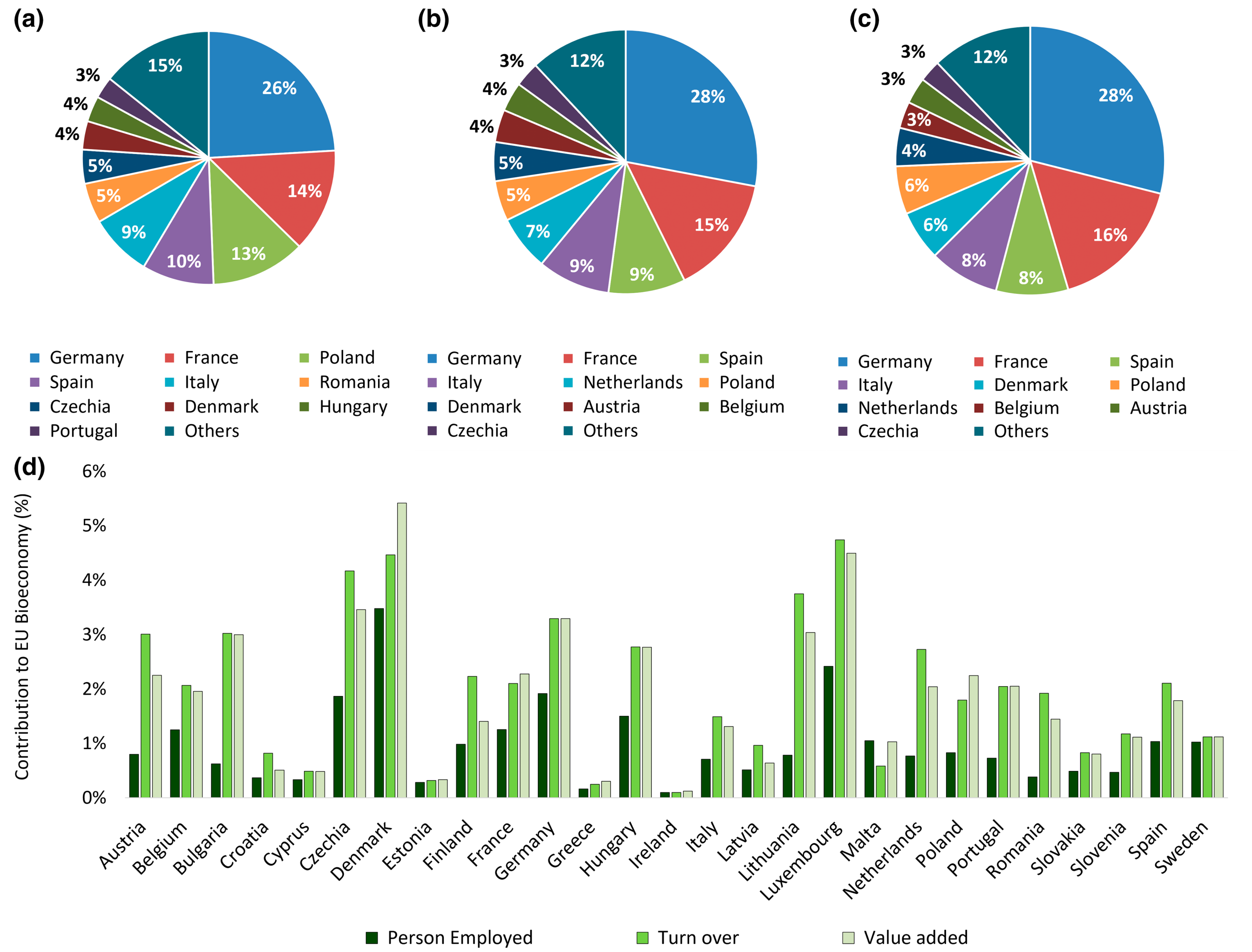

FIGURE 5 Contribution of each country to (a) persons employed, (b) turn over and (c) value added of the EU's bio-based chemical sector; and (d) contribution of the EU's bio-based chemical sector relative to the whole EU's Bioeconomy sector. *Source*: López et al. (2022).

sites, including prevention measures against pollution (i.e., reduce and recycle wastes, and proper waste disposal). The best available techniques (BATs) ensure efficient energy use, prevention of accidents and to help lower GHG emissions, pollution, and waste generation (EC, 2023d).

From the European Green Deal, several other directives, plans, and strategies were elaborated, such as the "Circular Economy Action Plan" (EC, 2020b) that provides a future-oriented agenda for achieving a cleaner and more competitive EU in co-creation with economic actors, consumers, citizens, and civil society organizations. Following up on the Circular Economy Action Plan, a directive that bans single-use plastics and bags was launched in 2021, and the Sustainable Product Initiative was launched in 2022 (EC, 2021b). The "Chemicals Strategy for Sustainability Towards a Toxic-Free Environment" aims at reducing the risks to humans and the environment posed by certain hazardous chemicals, such as carcinogens and heavy metals (EC, 2020a). The safe and sustainable-by-design framework was established to ensure the production of non-toxic material cycles, innovating industrial production, strengthening the EU's open strategic autonomy, protection against the most harmful chemicals, endocrine disruptors, chemical mixtures, and chemical pollution in the natural environment (EC, 2020a). New chemicals and materials must be inherently safe and sustainable, from production to end-of-life, while new production processes and technologies must be deployed to allow the chemical industry's transition to climate neutrality (EC, 2020a).

More recently, three important sustainability initiatives for the chemicals and plastics sector were released. The "Chemicals in Plastics – A Technical Report" from the United Nations Environment Programme (UNEP, 2023) explores chemical-related pollution and its impacts on human health. The "Transition Pathway For The Chemical Industry," published by the European Commission, identifies actions to achieve the twin transition, while improving the resilience of the sector in three main pillars, collaboration for innovation, clean energy supply, and feedstock diversification (EC, 2023a). Finally, the global agreement to end plastic pollution adopted during the United Nations Environmental Assembly in 2022 (UNEA, 2022).

In the last two decades, waste generation dropped one third, accidental pollutant releases decreased by 40%, acidifying emissions reduced by 70%, emissions of water pollutants reduced by half, and non-methane volatile organic compound and methane emissions dropped by 70% (CEFIC, 2022). Landfilling of plastic waste reduced by 47%, recycling increased by 117%, and exports of plastic wastes reduced by 50% (PlasticsEurope, 2022). However, there is a long road ahead to improve plastics end-of-life, mainly the waste collection and sorting. Currently, most of plastic waste collected in the EU is incinerated (42%) and Finland leads the ranking with nearly 80% of its collected plastic waste ending up in incineration facilities with energy recovery (PlasticsEurope, 2022). Only 35% of the collected plastic waste is recycled in the EU (PlasticsEurope, 2022) and none of the European countries have recycling as the major end-of-life treatment; the Netherlands has the highest recycling share of 45%. Around 23% of EU plastic waste is still sent to landfills on average, while in specific EU areas like Malta and Greece up to 75% of plastic waste is landfilled (PlasticsEurope, 2022). The current collection and sorting of plastic makes it inefficient to recycle and favors incineration. Half of the collection of plastic waste happens via dedicated plastic collection and half via mixed waste collection. The dedicated plastic collection has a better rate of recycling (65%) compared to only 5% when the plastic is mixed with other wastes. Most of the plastic in mixed waste collection ends up in incineration for energy recovery (57%) and landfill (38%), against only 27% and 8% for energy recovery and landfill, respectively, when dedicated collection happens (PlasticsEurope, 2022).

2.6 | The EU chemical sector in a global context

The EU is a net exporter of chemicals and plastics, with the largest importers being the United States and the United Kingdom (CEFIC, 2022; PlasticsEurope, 2022), but has a trade deficit (i.e., imports more than exports) with Switzerland and, more recently, with China (CEFIC, 2022; EC, 2023b). Conversely, the EU chemical sector has been shrinking and has faced a sales reduction over the past two decades (CEFIC, 2022; EC, 2020a). Currently, the EU has only a 14% share of global chemical sales, but this share was 25% two decades ago (CEFIC, 2022). Projections suggest that by 2030, the EU will lose its second position in the global ranking, having only 10% of the global market share, becoming the third world's largest chemical producer, behind China and the United States (CEFIC, 2022; EC, 2020a). The EU is experiencing a decline in its share of high-value chemical production (i.e., ethylene, propylene, benzene, toluene, and xylene), ammonia and methanol, which represent only 15%, 12% and 3%, respectively, of the global production (OECD/IEA, 2018). The most affected subsectors are the production of plastics in primary forms followed by organic basic chemicals, paints, varnishes, and similar coatings; printing ink; soaps, detergents, cleaning preparations, and polishing preparations; and perfumes and toilet preparations (EC, 2016). In the last decade, the number of enterprises and individuals employed in the EU chemical sector increased by only 5% and 2%, while the turnover and production value decreased by 0.9% and 1.7%, respectively (Eurostat, 2023a). Possible explanations for this decrease include comparatively smaller investment in research and innovation than in China and the NAFTA zone. Capital investments in China's chemical sector are 78% higher than in the EU, while for research and innovation, 32% more is invested (CEFIC, 2022).

3 | CHALLENGES AND OPPORTUNITIES FOR A BIO-BASED CHEMICAL SECTOR

3.1 | Circular economy

3.1.1 | Challenge: Biomass availability

A large-scale production of bio-based chemicals and plastics requires substantial feedstock. Currently, even with the very low share of bio-based chemicals and plastics, the EU already relies on imports of biomass, having most of its vegetable oil coming from outside EU borders (Spekreijse et al., 2019; Spierling et al., 2018).

Biomass needs to be sustainably sourced to be aligned with the EU's Bioeconomy Strategy and the European Green Deal, and to avoid competition with food production (EC, 2018b; Rosenboom et al., 2022). However, biomass is also demanded in other industrial sectors, for example, energy, iron and steel, cement, and transport, and the utilization of the higher potential estimates may trigger degradation of ecosystem services. In the chemicals sector, carbon is not only used as an energy source, but it is also present in the product structure, which limits the alternative renewable feedstocks to replace fossil carbon. The chemical sector can thus not achieve decarbonization but should aim at defossilization.

3.1.2 | Opportunity: Biomass potentials and alternative feedstocks

In the EU, there is a potential of around 123.5 Mt dry basis of crop residues considering sustainable recovery rates that avoids reduction of soil carbon stocks (Scarlat et al., 2019), and 36.0 Mt (dry basis) of forest residues, under sustainable forest management excluding protected areas (Verkerk et al., 2019). Their technical potential can replace all the fossil ethylene and fossil methanol annually produced in the EU, 13 and 1.7 Mt, respectively (Eurostat, 2023c). This estimation considers 0.11 kg ethylene per kg of lignocellulosic feedstock (Akmalina & Pawitra, 2020; Morales et al., 2021) and 0.63 kg of methanol per kg of lignocellulosic feedstock (Fournas & Wei, 2022).

Although less explored for chemicals production, lignin has great potential to directly replace fossil platform chemicals and to produce novel bio-based polymers with equivalent or similar functionalities. The pre-treatment of lignocellulosic feedstock presents considerable challenges, which are intensified by the necessary lignin depolymerization (Li et al., 2019). There are pathways to valorize the lignin in a biorefinery context, such as the "lignin-first approach" (Cao et al., 2019; Tschulkow et al., 2024), but there is still large room for lignin valorization (Velvizhi et al., 2022). Vanillin is the only lignin-based chemical produced on a commercial scale (Borregaard, 2023). Innovative lignin-based chemicals include polyurethane coatings (De Haro et al., 2019) and methacrylates with high glass transition temperatures (Bonjour et al., 2021; Kakuchi et al., 2021). Around 170 Mt of black liquor are generated annually in the global pulp and paper industries (IEA Bioenergy, 2013). Using about 30% of it could replace the annual production of polystyrene, polymethyl methacrylate and polycarbonate in Europe (3.4, 1.2, and 0.1 Mt, respectively) (Eurostat, 2023c) with a bio-based polymer derived from vanillin. This considers black liquor containing around 36% of lignin (Reyes et al., 2020) and 0.06 kg of the bio-based polymer per kg of lignin (Souza et al., 2023). However, most lignin is currently burnt to provide heat and power in the pulp and paper industries (Li & Takkellapati, 2018) and in biorefineries (Kapanji et al., 2021).

Organic wastes, for example, municipal organic waste, agro-industrial wastes, used cooking oil, and industrial food wastes have potential as feedstock for chemical production. Bio-based chemicals from organic wastes, currently underutilized or unutilized, can contribute to climate change mitigation (Leong & Chang, 2022; Manhongo et al., 2021) while alleviating potential trade-offs associated with land-based biomass and potentially induced direct or indirect land use changes. Commercial technologies for converting organic wastes are often applied for bioenergy purposes, while those targeting bio-based chemicals are still at a low TRL (Javourez et al., 2022; Jin et al., 2020; Kang et al., 2022). About 58 Mt of food waste is generated annually in the EU, half of it is enough to replace the total 9 Mt of fossil polypropylene produced in the EU annually (Eurostat, 2023c) with polyhydroxyalkanoate, a bio-based polymer with properties and function similar to polypropylene (Acharjee et al., 2023). This considers 0.32 kg of polyhydroxyalkanoate per kg of food waste (Colombo et al., 2017).

Macroalgae have great potential to produce bio-based chemicals and plastics (Ayala et al., 2024), this blue biomass provides low carbon plastics without land use (Ayala et al., 2023a). Microalgae are also a viable bio-based feedstock as they have a distinct composition (pigments, lipids, proteins and carbohydrates) that may fulfill the need for sustainable sources of energy, food and chemicals (Giraldo-Calderón et al., 2018). Microalgae production is comparable to conventional agriculture; however, microalgae have a higher areal productivity, and they are produced in non-arable land (Sahni et al., 2019). The EU microalgae sector is at its early stages, about 182 t (dry matter) of microalgae and 142 t (dry matter) of Spirulina are currently produced annually (Araújo et al., 2021). In Europe, microalgae biomass is typically used in the formulation of food supplements (24%), cosmetics (24%), and feed (19%) (Araújo et al., 2021). Regarding Spirulina, the most predominant applications (75%) are in food, food supplements and nutraceuticals (Kuech et al., 2023). However, an increase in the market size could provide room for chemicals and plastics production, including pharmaceutical applications.

Another option is the production of chemicals directly from carbon dioxide (CO_2) via carbon capture and utilization (CCU) technologies (EC, 2023c; Thonemann & Pizzol, 2019). Potential CO_2 sources include biogenic gaseous carbon, industrial off-gases from food, beverages, and biofuel fermentation processes (EC, 2023a), and from coke oven gas released in iron and steel factories (OECD/IEA, 2018). However, CO_2-based chemicals still face some challenges, considering the high complexity, costs, and energy required to collect and purify CO_2 directly from the air (EC, 2023a).

Exploring locally produced lignocellulosic residues (Scarlat et al., 2019; Verkerk et al., 2019) and combining multiple renewable raw materials is key to ensuring feedstock availability for the chemical sector (Bachmann et al., 2023). Recycled chemicals from plastic waste are one alternative to increase feedstock availability, as most polymers can be transformed back into monomers and building blocks (Lange, 2021). However, currently only 10% of total plastic produced in the EU comes from recycled plastic waste (PlasticsEurope, 2022). Efforts are needed to improve the plastic waste sorting, collection, and recycling, to develop new technologies that can upgrade mixed plastics and hard-to-recycle plastics into new products, and to reduce the production and consumption of some plastic types, as packaging (EC, 2023a).

3.2 | Contribution to climate neutrality, toxic-free chemicals, and end of pollution

3.2.1 | Challenges for sustainable bio-based value chains

Bio-based chemicals and plastics are not necessarily more sustainable than fossil-based chemicals and plastics (Souza et al., 2023; Zuiderveen et al., 2023). The sustainability of bio-based chemicals and plastics depends on the method used for their assessment and on a wide range of conditions along their life cycle, from the biomass production, industrial conversion, up to the end-of-life, and these conditions can offset the potential sustainable benefits that bio-based products can offer when replacing their fossil counterparts (Rosenboom et al., 2022). In the fossil-based value chain, the most produced chemicals and plastics (Section 2.2) are derived from ethylene, propylene, benzene, toluene, xylene, hydrogen, methanol, and ammonia (Figure 6a). These chemicals can be produced from biomass via different pathways such as biochemical and/or thermochemical routes and can directly replace their fossil counterparts; these are known as drop-in chemicals (Figure 6b). Bio-based value chains can also generate a large range of dedicated plastics through various pathways (Figure S1). However, if not properly designed, the value chain of bio-based chemicals and plastics can result in climate change, toxicity and pollution impacts similar to, or even greater than, those of their fossil counterparts.

The main goal of a biorefinery is essentially to add hydrogen and remove all (or most) of the oxygen in the original biomass. While fossil fuels have no oxygen, biomass has too much of it. Hence, it requires considerable amounts of hydrogen as input in a large-scale bioeconomy. But the integration with sustainable hydrogen value chains can be a challenge, as the current hydrogen production pathways are mostly fossil-based (Qureshi et al., 2022; Wei et al., 2024). Also, bio-based value chains add several steps compared to conventional fossil production of chemicals. The biomass pre-treatment and the further purification of the targeted chemicals face several technical barriers on a commercial scale (EC, 2021a). The variability of biomass quality and the reduced cost-competitiveness due to low oil prices challenge the feasibility of bio-based chemicals production (EC, 2021a).

Most bio-based production processes are still not as mature as commercial fossil ones and can be less efficient in terms of energy consumption, resource efficiency, and economic feasibility, among others (EC, 2021a; Rosenboom et al., 2022). For some applications, the bio-based alternatives are emerging technologies at a very low TRL. This is the case for bio-based polymers with a high glass transition temperature, high crystalline melting point, and high molecular weight (Nguyen et al., 2018). Thus, high investments are necessary to scale-up low TRL technologies to a commercial scale. But given the innovative nature, these investments carry high risks and face challenges in obtaining funding, due to the requirements for market size, financing, and technical issues (Pizzol & Andersen, 2022).

Finally, the upstream of bio-based chemicals and plastics can be designed to ensure better degradability, recyclability, and composability (Demarteau et al., 2023). However, unless properly managed and treated, the downstream of bio-based plastics will continue causing pollution (Stanton et al., 2021). The substantial amounts of plastic and microplastic debris polluting rivers and marine ecosystems are a consequence of inadequate plastic waste management practices (Chowdhury et al., 2023; EEA, 2020) and simply replacing fossil with biomass feedstocks, without closing the loop at the end-of-life of plastics, will not effectively mitigate plastic pollution (Fagnani et al., 2021; Kakadellis & Rosetto, 2021).

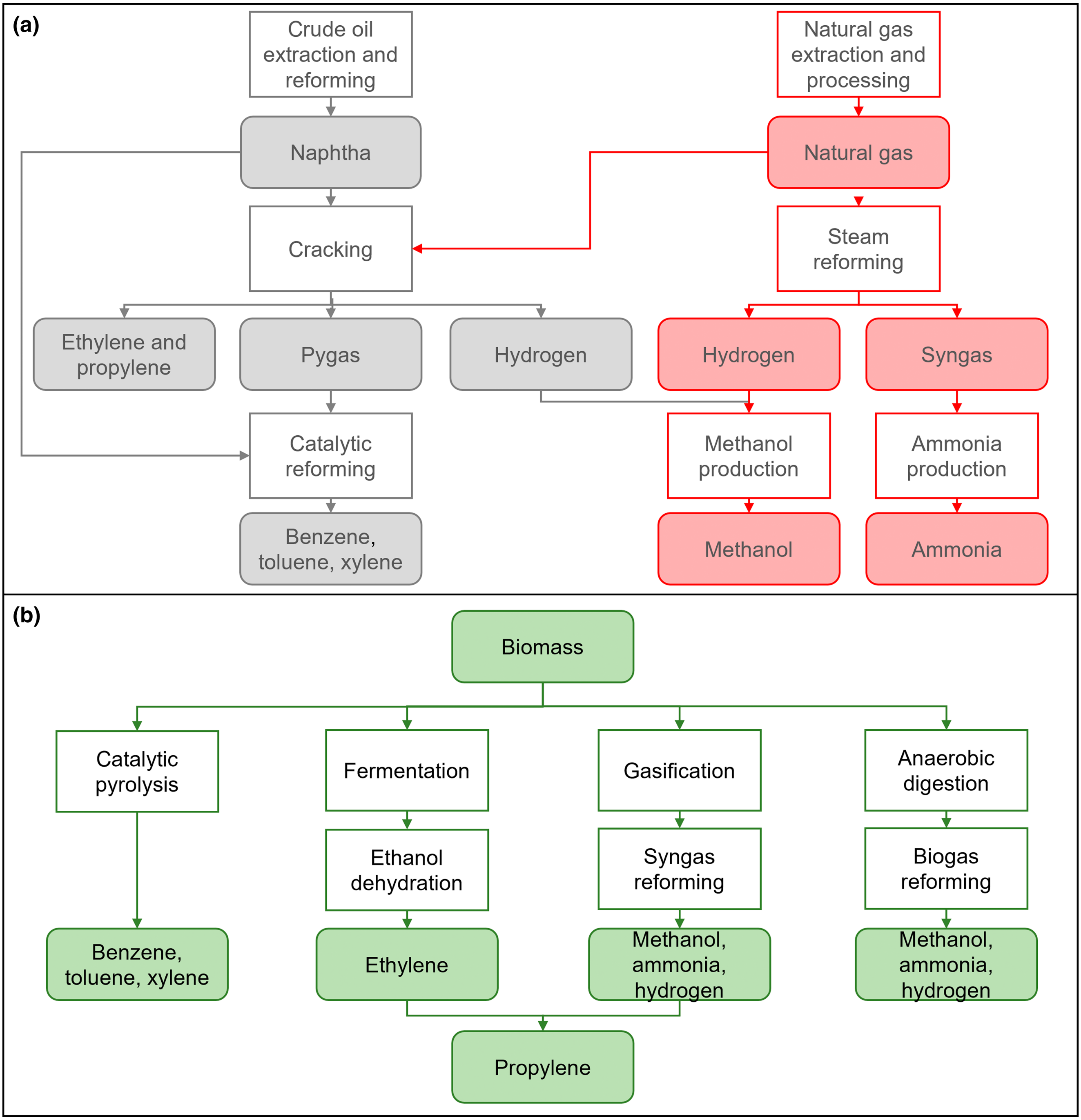

FIGURE 6 Simplified value chains to produce the main fossil chemicals (a), and potential pathways to produce their bio-based drop-ins (b).

3.2.2 | Opportunities for sustainable bio-based value chains

There are potential ways to overcome the sustainability challenges of bio-based plastics and chemicals. Chemicals can be produced in dedicated plants or in a biorefinery concept integrated with biofuels and bioenergy production, benefiting from the strong knowledge and infrastructure available (EC, 2021a). The integration with large-scale produced biofuels, as in the case of sugarcane-derived bioethylene (Brasken, n.d.) and sugarcane-derived polylactic acid (Bressanin et al., 2022), provides the cascade use of biomass, enables circularity, and adds value to biomass (Lindorfer et al., 2019). Most of the biorefineries are currently producing biofuels, but recently more attention has been given to high-value bio-based chemicals (EC, 2021a). This is a transition from using biomass for low-value products targeting the energy and transport sectors to high value products targeting several other markets, for example, polymers, paints, cosmetics (Pizzol & Andersen, 2022).

The production of key platform chemicals (e.g., sugars, pyrolysis oil, syngas, biogas, lignin, CO_2, glycerol, etc.) brings flexibility to the plant and are commercial technologies (Jong et al., 2020). These platform chemicals are intermediates for several chemicals, polymers, but also for fuels, and can be produced via thermochemical (e.g., pyrolysis, gasification), biological (fermentation, anaerobic digestion), and oil fractionation conversion pathways (Jong et al., 2020). The platform chemical concept is similar to the fossil refineries that operate from a key set of common feedstocks (Section 2.1). This flexibility can ensure adaptation to market conditions, demands, and seasonality in feedstock availability, as consolidated with sugarcane biorefineries in Brazil that continuously adjust the shares of their alternative products (i.e., sugar, bioethanol, electricity, etc.) (Souza et al., 2018).

Although drop-in chemicals provide the same chemical molecule as their fossil counterparts, no advantages in terms of toxicity and degradability can be provided. However, the development of dedicated chemicals and plastics can bring environmental advantages against their fossil counterparts, such as recyclability and biodegradation (Rosenboom et al., 2022; Xia et al., 2021) and lower toxicity (Ismagilova et al., 2023).

An emerging area of sustainable feedstock for the chemical sector is the production of algae, but there are some necessary improvements and challenges to be overcome before its large-scale production. These include industrial optimization (Ayala et al., 2024), consistent biomass supply throughout the year (Araújo et al., 2021), and techno economic feasibility (Kuech et al., 2023). Currently, it is noticed that private investment in the algae sector often awaits a robust market signal indicating the demand of algae biomass-based products.

Finally, the planning and integration of the growing bioeconomy with sustainable hydrogen value chains is key for the de-fossilization of the chemical sector. This integration requires clean electricity sources (i.e., solar, wind, biomass), carbon capture and storage technologies, and sustainable bio-based pathways (e.g., gasification, pyrolysis) for the hydrogen production (Qureshi et al., 2022).

3.3 | Sustainability assessment of bio-based chemicals

3.3.1 | Challenges in the sustainability assessment of bio-based chemicals

The production processes of several bio-based chemicals and plastics are still at a low TRL and limited knowledge about their industrial-scale performance hinders the assessment of their socioeconomic and environmental impacts (Javourez et al., 2022; Manhongo et al., 2021). There are different approaches for scaling-up low TRL technologies in environmental assessments (Souza et al., 2023) and no official standardization from the EU, which hinders robust sustainability assessments.

The potential new functionalities of bio-based chemicals and plastics compared to conventional fossil counterparts challenge the definition of system boundaries and generate multi-function units when co-producing fuels, chemicals, and electricity (Ayala et al., 2023b; Cucurachi et al., 2022).

The biogenic carbon content embedded in the chemicals and plastics brings great potential for GHG mitigation, but carbon dynamics depend on the type of biomass, time dynamics, product stock, and the end-of-life of the bio-based product (Arehart et al., 2021), and varying results can be obtained from different approaches. Initiatives to harmonize the carbon dynamics and biogenic carbon accounting are being developed (Cucurachi et al., 2022).

Chemicals and plastics contribute to the triple planetary crisis (Hellweg et al., 2023), exceeding the safe operating space of several planetary boundaries (Bachmann et al., 2023; Meng et al., 2023; Tulus et al., 2021). But harmonized methods to measure pollution (Askham et al., 2023) and toxicity (Sørensen et al., 2023) impacts against fossil counterparts are lacking. Finally, few studies assess social impacts of bio-based chemicals and plastics, calling for more research in this topic (Falcone & Imbert, 2018; Spierling et al., 2018).

3.3.2 | Opportunities in the current EU sustainability initiatives

Although most of the current EU sustainability initiatives are not exclusively dedicated to bio-based chemicals and plastics production (Section 2.5), they can provide opportunities to strengthen and develop a circular bioeconomy in the EU chemical sector (Tables 3 and S6). The EU has a dedicated Bioeconomy Strategy and Action Plan that can strengthen

TABLE 3 Exploring opportunities for a bio-based chemical sector in the existing European sustainability initiatives.

Opportunities	EU sustainability initiatives
Cascade use of biomass, valorization of secondary, residual, and waste biomass to produce bio-based chemicals	• A European Strategy for Plastics in a Circular Economy • Chemicals Strategy for Sustainability Towards a Toxic-Free Environment • Circular Economy Action Plan • Climate Target Plan • EU Methane Strategy • European Critical Raw Materials Act • Implementation of EU ETS—Phase 4 • Recovery plan for Europe Next Generation EU • Renewable Energy Directive (recast)—COM (2021) 557 final • Stepping up Europe's 2030 climate ambition: Investing in a climate-neutral future for the benefit of our people • Strategic research and innovation plan for safe and sustainable chemicals and materials • Sustainable Carbon Cycle • Building the future with nature: Boosting Biotechnology and Biomanufacturing in the EU • Regional Innovation Valleys for Bioeconomy and Food Systems
Develop non-hazardous and non-toxic bio-based chemicals	• Bioeconomy Strategy and Bioeconomy Action Plan • Chemicals Strategy for Sustainability Towards a Toxic-Free Environment • Corporate Sustainability Due Diligence • EcoDesign for Sustainable Products Regulation (ESPR) • EU Biodiversity Strategy for 2030 • Farm to Fork Strategy • IED—Industrial Emissions Directive's revision • Revision of CLP—Classification, Labelling and Packaging • Revision of REACH • Revision of the Environmental Crime Directive • The Eco-design for Sustainable Products Regulation: update 2009 • Zero Pollution action plan
Recyclable, biodegradable, and compostable bio-based chemicals	• A European Strategy for Plastics in a Circular Economy • Bioeconomy Strategy and Bioeconomy Action Plan • Chemicals Strategy for Sustainability Towards a Toxic-Free Environment • Circular Economy Action Plan • EcoDesign for Sustainable Products Regulation (ESPR) • UNEA Resolution "End plastic pollution: Towards an international legally binding instrument" • EU policy framework on bio-based, biodegradable and compostable plastics
Develop low-carbon bio-based chemicals	• Bioeconomy Strategy and Bioeconomy Action Plan • Circular Economy Action Plan • Corporate Sustainability Due Diligence • EcoDesign for Sustainable Products Regulation (ESPR) • Farm to Fork Strategy • Waste gas in the chemical industry • Building the future with nature: Boosting Biotechnology and Biomanufacturing in the EU • The Net-Zero Industry Act
Develop novel and advanced bio-based chemicals and materials from sustainably sourced biomass	• Climate Target Plan • EU Advanced Materials and Chemicals Manifesto • EU strategic dependencies and capacities: second stage of in-depth reviews • European Climate Law • Building the future with nature: Boosting Biotechnology and Biomanufacturing in the EU • The Net-Zero Industry Act • Regional Innovation Valleys for Bioeconomy and Food Systems
Sustainably sourced biomass as energy and feedstock source for the chemicals sector	• Climate Target Plan • European Climate Law • Stepping up Europe's 2030 climate ambition: Investing in a climate-neutral future for the benefit of our people • Sustainable Product Initiative

(Continues)

TABLE 3 (Continued)

Opportunities	EU sustainability initiatives
	• Building the future with nature: Boosting Biotechnology and Biomanufacturing in the EU • The Net-Zero Industry Act • Regional Innovation Valleys for Bioeconomy and Food Systems
Better labeling of bio-based chemicals and their potential environmental advantages	• EU taxonomy for sustainable activities • EU policy framework on bio-based, biodegradable and compostable plastics • Green Claims Directive • Law banning greenwashing and misleading product information
Use the sustainable biomass criteria from biofuels to bio-based chemicals and materials	• EU sustainability criteria for bioenergy • Renewable Energy Directive (recast)—COM(2021) 557 final • EU policy framework on bio-based, biodegradable and compostable plastics • Building the future with nature: Boosting Biotechnology and Biomanufacturing in the EU

and scale up the bio-based sector, while deploying local bio-economies within ecological boundaries (EC, 2018b). Most of the initiatives directly encourage the use of biomass as feedstock for chemical production, contributing to a circular economy, for example, the "Circular Economy Action Plan" and "Sustainable Carbon Cycle." While others provide opportunity to develop non-hazardous and non-toxic bio-based chemicals, for example, "Chemicals Strategy for Sustainability Towards a Toxic-Free Environment," and recyclable and biodegradable chemicals, for example, "EcoDesign for Sustainable Products Regulation."

There are, however, five main issues that should be better addressed by the EU sustainability initiatives that are specific for bio-based chemicals and plastics. They are (I) an unbalanced higher number of initiatives aiming at climate change mitigation compared to reduction of plastic pollution, for example, what calls for more actions in this regard. (II) Lack of proper standards on how to deal with bio-based plastic waste. Most bio-based plastics are currently not recycled although they are technically recyclable (Rosenboom et al., 2022). (III) Less attention is given to the need of being transparent about the potential advantages and benefits of bio-based products in the chemical sector so that they are developed and commercialized (Simon et al., 2021). Inconsistent labeling, contradicting life cycle assessments and "greenwashing" are among the consequences of a lack of information related to bio-based chemicals and bio-based plastics (Rosenboom et al., 2022). The recent law adopted to ban greenwashing and misleading product information in the EU can help achieving a better labeling of bio-based products (European Parliament, 2024). (IV) Lack of harmonization and standardization of sustainability assessment of bio-based chemicals and plastics. This includes how to scale-up low TRL technologies, how to account for and calculate biogenic carbon flows, and methods to measure associated toxicity and pollution from chemicals and plastics. (V) There are no standards specifying the extent of improvements from bio-based chemicals and plastics against their fossil equivalents, as the ones from biofuels (i.e., EU sustainability criteria for bioenergy and Renewable Energy Directive). Unless bringing improved functionalities, bio-based plastics can have the same impact on human health, marine pollution, and waste generation (i.e., if not recyclable) as their fossil counterparts (Nielsen et al., 2019; Stanton et al., 2021). Identifying sustainability benefits and trade-offs provides a means to reduce potential adverse impacts of bio-based chemicals and plastics production.

4 | CONCLUSION

We critically review the opportunities and challenges of a bio-based chemical sector in the EU, with more details on the plastics sector. An overview of the current chemical sector showed that the bio-based share of total chemical production is currently very low (3%), but the EU has potential to become more bio-based. Currently, the chemical sector represents less than 1%, in average, of the value added, turn over and persons employed of the EU's Bioeconomy. Germany, Italy, France, Spain, and Netherlands are key countries to produce bio-based chemicals and plastics, offering great opportunity for a circular bioeconomy. Germany, for example, produces 35% of the EU's fossil hydrogen, ethylene, and propylene, and 26%–28% of EU's value added, turn over and persons employed in the bio-based sector. The main opportunities and challenges for this large-scale transition are biomass availability, value chain design and sustainability assessment of bio-based chemicals and plastics. The availability of biomass can be overcome by exploring different lignocellulosic feedstock locally sourced, organic wastes, algae, and improving plastic recyclability. The available crop and forest residues in the EU could replace all the fossil ethylene and methanol produced annually, and half of the EU's food waste could replace all fossil polypropylene produced in the EU. The production of value-added chemicals in biorefineries, integrated into biofuels, can benefit from the commercial knowledge and infrastructure available, while cascading the use of biomass. The reduction of toxicity can be achieved by developing dedicated chemicals and plastics, but the reduction of pollution is dependent on waste management and not only on the development of bio-based chemicals with better recyclability and biodegradability.

There is a need for sustainability initiatives dedicated to bio-based chemicals plastics, ideally coupling the growing bioeconomy and hydrogen-economy. This includes the assessment of other impacts beyond climate change mitigation (e.g., plastic pollution, toxicity) and of socioeconomic impacts; standards of how to deal with bio-based plastic waste; transparent labeling of bio-based products; harmonization and standardization of scaling-up low TRL technologies, biogenic carbon calculation, and methods to measure toxicity and pollution; and standards specifying the extent of improvements from bio-based chemicals and plastics against their fossil counterparts. The development of a circular bioeconomy in the EU chemical sectors requires significant investments, ongoing innovation, and collaborative efforts among citizens, academia, policy makers, and the industry.

AUTHOR CONTRIBUTIONS

Nariê Rinke Dias de Souza: Conceptualization (lead); formal analysis (lead); investigation (lead); methodology (lead); resources (lead); visualization (lead); writing – original draft (lead); writing – review and editing (lead). **Marisa Groenestege:** Conceptualization (supporting); methodology (supporting); visualization (supporting); writing – original draft (supporting); writing – review and editing (supporting). **Jurjen Spekreijse:** Resources (supporting); validation (supporting); writing – original draft (supporting); writing – review and editing (supporting). **Cláudia Ribeiro:** Investigation (supporting); writing – original draft (supporting). **Cristina T. Matos:** Investigation (supporting); writing – original draft (supporting). **Massimo Pizzol:** Funding acquisition (lead); project administration (lead); writing – review and editing (supporting). **Francesco Cherubini:** Methodology (supporting); supervision (lead); validation (supporting); writing – review and editing (supporting).

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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SUPPORTING INFORMATION

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