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Survey of Green Platform Chemicals

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Kurzfassung

Trotz des riesigen Fortschritts den Chemikalien Politik in den letzten Jahren erreicht hat bei der Kontrolle der Risiken von Chemikalien, stellen die Nutzung fossiler Ressourcen sowie Umweltverschmutzung durch Chemikalien zwei große Probleme dar, speziell im Kontext der dreifachen planetaren Krise. Daher berücksichtigt die Chemikalienstrategie für Nachhaltigkeit (CSS) die Transformation der chemischen Industrie in Richtung sicherer und nachhaltiger Chemikalien als große Herausforderung für die zukünftige Chemikalien Politik, Management und Industrie. Aus diesem Grund ist die Entwicklung von inhärent sicheren und nachhaltigen (SSbD) Alternativen sehr gefragt. Das Konzept der grünen Chemie war ein Meilenstein im Kontext der Transformation einer chemischen Produktion basierend auf fossilen Ressourcen und unter Verwendung von hochgradig gefährlichen Substanzen. In der Literatur ist der Begriff „Grüne Plattform Chemikalie" ein Schlüssel Konzept, welches die chemische Grundlage für einen alternativen Ansatz beschreibt. Während die Farbe Grün ein Symbol für Entitäten ist, welche aus der Natur stammen und daher von unserer Gesellschaft als grundsätzlich harmlos gesehen werden, zeichnen Substanzen wir Phyto- und Mykotoxine ein ganz anderes Bild. Dieses Klischee könnte genauso gut auf grüne Plattform Chemikalien zutreffen.

Diese Diplomarbeit zielt darauf ab, grüne Plattform Chemikalien aufgrund von öffentlichen zugänglichen Daten auf ihre Gefahren zu untersuchen. Zu diesem Zweck wurde einschlägige Literatur nach Vorschlägen für Plattform Chemikalien durchsucht und gelistet. Die Substanzen auf der Liste wurden dann auf ihr Gefahrenpotenzial und regulatorischen Aktivitäten untersucht mit Hilfe der öffentlichen Datenbank der europäischen Chemikalien Agentur (ECHA). Als vielversprechendes Ergebnis wurde festgestellt, dass 63 % der 131 untersuchten Substanzen relativ datenreich sind, da sie mit Produktion-/Importvolumen über 10 Tonnen pro Jahr registriert sind, und ein verhältnismäßig geringes Gefahrenpotential aufweisen, basierend auf dieser Untersuchung. Daher können diese bio-basierten Chemikalien potenziell als Ersatz für ihre gefährlicheren und weniger nachhaltigeren fossilen Äquivalenten dienen. Es wird empfohlen, dass die Annahme ihres niedrigen Gefahrenpotenzials weiter untersucht und bestätigt wird. Außerdem sollten diese Substanzen tiefer gehender Analysen, zum Beispiel Life-Cycle Analyse, unterworfen werden, um sie als SSbD Chemikalien für die chemische Industrie zu bestätigen. Die „relevantesten" Plattform Chemikalien für Wissenschaft und Industrie wurden ausgewählt und näher besprochen. Ein Teil dieser wird schon heute aus nachhaltigen Rohstoffen produziert.

Abstract

Despite the huge progress that chemical policy has achieved in the last years to control the risk of chemicals, fossil resources use as well as pollution by chemicals are still considered as two of the main concerns in the triple planetary crisis. Thus, the chemical strategy for sustainability (CSS) considers the transition of chemical industry towards safe and more sustainable chemicals as a major challenge for future chemical policy, management, and industry. For this reason, the development of safe and sustainable by design (SSbD) alternatives in the current chemical management are highly searched for. The concept of green chemistry has become an important innovation in this context aiming at the transformation of the current chemical production which is fossil based and involves substances bearing high hazardous potential. In the literature the term “green platform chemicals” has become a key concept describing the chemical bases for such an alternative approach. While the colour green symbolizes entities, which are derived from nature in our societies and therefore genuinely considered as benign for humans, examples like phyto- and mycotoxins are in strong contrast to that picture. This cliché may also apply to green platform chemicals.

Therefore, this work was aiming to investigate green platform chemicals with respect to their potential hazard based on existing and publicly available data. For this purpose, the literature has been searched for substances proposed as green platform chemicals. The identified list of substances has been further screened with respect to their hazardous properties and the regulatory activities using the European Chemicals Agency’s website as information bases. As a promising result, 63% of the 131 surveyed substances are relatively data rich substances (being registered as manufactured/imported in volumes higher than 10 tonnes per year in the EU) and are of comparatively low potential hazard based on this investigation. Therefore, these bio-based substances could potentially serve as substitutes for their more hazardous and less sustainable fossil equivalents. It is recommended that the assumption of these chemicals being of low hazard should be investigated and confirmed. Furthermore, these substances should be subject to an in-depth analysis e.g. life-cycle assessment to identify them as SSbD chemicals for industry. The “most relevant” platform chemicals for academia and industry were chosen to be presented in a short overview. A part of these are already produced from sustainable feedstocks.

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1. Introduction

During the 21st century, the term "green platform chemicals" (GPC) has become a key concept of an ecologically oriented chemistry and is considered to represent alternatives to classical petrochemical-based substances. Given the absence of a generally adopted formal definition of this term, the major objective of this work is to carry out a comprehensive survey of green platform chemicals referenced in the literature, together with a first assessment of these substances, aiming at the identification of existing information, possible data gaps, and future research directions to further concretise and operationalise the concept of GPC.

In this introduction, the subject of GPC should first be put in the larger context of the global sustainability crisis and the response provided by green and sustainable chemistry in the field of chemicals.

The triple planetary crisis of climate change, biodiversity loss, and pollution has become one of the most urgent topics in human history. The global resource outlook 2024 [1] by the United Nations sees circularity and sustainable biomass use as important aspects to combat these problems. This aim is also enshrined in the European Green Deal, which aims to transform the EUs linear economy into a circular and sustainable one by 2050 [2]. With respect to chemicals, the European Commission developed the chemicals strategy for sustainability (CSS) [3], which specifies on how to reach these goals in the chemical sector and making the production and use of substances safer and more sustainable.

The EU chemicals strategy for sustainability is a key document, which triggered a number of activities by the European commission. One of these is the revision of the REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) regulation [4], which came to a halt due to parliamentary elections and the reestablishment of the commission in 2024. The revision process will be continued in the coming years. A second important activity is the development of an assessment tool for safe and sustainable by design chemicals, which is currently in progress under the European research and innovation policy. Based on reports [5, 6] by the joint research centre (JRC), the European Commission has published, in 2022, the recommendation (EU) 2022/2510, establishing a European assessment framework for 'safe and sustainable by design' (SSbD) chemicals and materials. This recommendation invites member states, industry, academia and R&D organizations to implement and test the SSbD methodology developed by the JRC [7]. The JRC also carries out regular workshops with industry, NGOs and national experts aiming at the improvement of the SSbD assessment concept. Most recently, a methodological guidance has been published [8].

Under the research and innovation funding programme horizon Europe the 'partnership for the assessment of risks from chemicals' (PARC) has been established in May 2022 as a 7-year research partnership with a total funding volume of €400 million and 200 participating European organizations. Its objective is the development of next-generation chemical risk management by creating new data, knowledge methods and tools, expertise and networks. PARC intends to support the CSS and the European green deal and help to protect human health and the environment with its work. An important instrument currently developed in PARC is the SSbD toolbox, which aims to support the operationalisation of the SSbD framework of the European Commission. The toolbox development involves the identification and setting up of relevant use cases, the testing of the applicability of the SSbD criteria and methodology, and the establishment of an inventory of relevant indicators. It also includes knowledge sharing and guidance in SSbD, as well as providing training and educational materials [9, 10].

Apart from the developments described above, which directly apply to chemicals, the regulation (EU) 2024/1781 [11] establishes a framework for the setting of eco-design requirements for sustainable products (ESPR). The regulation entered into force in July 2024 and will certainly have significant impacts on the management of chemicals and chemical mixtures. The ESPR is part of a package of measures that are central to achieving the objectives of the 2020 circular economy action plan [12]. The regulation defines, inter alia, a new class of chemicals called "substances of concern" (SOC), the tracing of which in products along the supply chain is a key innovative part of the ESPR.

The current crisis clearly asks for more fundamental changes in chemicals management, including the necessary introduction of circularity, energy efficiency, and the transition to sustainable raw materials as main elements in future chemical production. Already in the 1990s this idea has been conceptualized by two innovative American chemists in a small booklet, becoming quickly the carta of green chemistry, as further detailed in section 3.

2. The current regulatory framework for the assessment of chemicals

The REACH regulation, governing the registration, evaluation, authorisation and restriction of chemicals, was adopted in 2006 by the European Parliament and European Council, and represents the central piece of chemical legislation within Europe. Its main goal is to ensure a high level of protection of human health and the environment as well as the free movement of substances, on their own, in mixtures and in articles, while enhancing at the same time competitiveness and innovation. Under REACH, most of the substances produced in or imported into the EU above one ton must be registered by the manufacturers or importers by submitting a dossier to the European Chemicals Agency (ECHA). The information required for the registrations differs, depending on the tonnage produced/imported, but generally covers the substance uses, exposure and its intrinsic hazards. Registrants of substances have to carry out comprehensive risk assessments which should ensure that all potential uses of the registered chemical in the value chain are safe with respect to human health and the environment. The data provided by the companies is evaluated by ECHA and the member states to ensure its completeness and quality. Substances exempt from the registration requirements are listed in Annex IV, which includes those important in food and feed (e.g. sugars and amino acids).
If a substance is identified as 'substance of very high concern' (SVHC) in accordance with the criteria established under REACH, authorisation is considered as a risk reduction measure under REACH. A member state or ECHA (on behalf of the European Commission) can propose the identification of a substance as SVHC, if it fulfils the criteria of being carcinogenic, mutagenic or toxic for reproduction (CMR) category 1A or 1B (in accordance with CLP), or as persistent, bioaccumulative and toxic (PBT), or very persistent and very bioaccumulative (vPvB), or because it causes an equivalent level of concern (e.g. endocrine disruption or respiratory sensitisation). Once a substance has been identified as SVHC by the member state committee in ECHA, the substance is included in the so-called 'candidate list' which is publicly accessible on ECHA's website (https://echa.europa.eu/candidate-list-table). Such substances are candidates for the inclusion in the authorisation list in annex XIV of REACH, based on a number of priority criteria defined in the regulation. The use of a substance, which is listed in annex XIV, requires, as from a certain date called sunset-date, an authorisation by the Commission.
Another possibility for managing the risk of substances under REACH is restriction of production, marketing and/or use. REACH establishes two different types of restrictions. For substances, the use of which leads to an unacceptable risk for human health or the environment, these uses can be restricted, following a comprehensive assessment by ECHA, member states and the commission. This procedure usually ends with the inclusion of the substance in annex XVII of REACH, specifying the scope of the restriction. For substances, which have CMR properties, and thus are particularly hazardous for humans, REACH empowers

the commission to directly propose an inclusion in annex XVII, restricting the use of this substances as such or in mixtures by the public. [4]
The classification of a substance is thus a significant trigger for risk management measures under REACH. The basis of the hazard classification in the EU is the so-called classification, labelling and packaging (CLP) Regulation, which essentially adopts the united nations' globally harmonised system (GHS) within the EU. Its main purpose is to harmonise hazard classification not only within the European market but also world-wide to ensure proper hazard management and the free movement of substances, mixtures and articles. It standardises the classification of hazards, but it also introduces phrases and pictograms for labelling. Harmonised classification and labelling (CLH) can be proposed by member state competent authorities. Manufacturers, importers or down-stream users may also trigger a CLH, but in the current system they can only apply for changes of an existing classification via a national competent authority. A positive decision on harmonisation leads to the inclusion of the substance in annex VI to CLP. Manufacturers, importers and down-stream users must classify their substances in accordance with annex VI and self-classify additional hazards not yet included in the annex VI. All classifications can be found in the classification and labelling (C&L) inventory held by ECHA. In 2022 the CLP regulation has been amended to include new hazard classes for endocrine disruption (ED), PMT (persistent, mobile, toxic), vPvM (very persistent, very mobile), PBT and vPvB. The new classification and labelling for substances in circulation must be applied latest from November 2026 and May 2025 for new products on the market. [13, 14]

The ECHA publishes all public data and processes concerning chemicals on its website. The 'public activity coordination tool' (PACT) is a digitalized database summarising the activities on substances under REACH and CLP currently carried out by ECHA or member states. Processes included are dossier evaluation (DEv), substance evaluation (SEv), informal hazard assessment concerning PBT, vPvB and ED properties, CLH, SVHC identification, recommendations for inclusion on the authorisation list (Recom), restriction, and assessment of regulatory needs (ARN). The database also includes entries for those substances, for which activities have already been finalised, together with the conclusions followed from the exercise. It is thus a very valuable information basis for risk-related actions on chemicals in the EU.

In the CSS [3] the commission proposed the definition of "most harmful chemicals" (MHC) to create a framework for the phasing out of the most problematic chemicals. The commission also introduced the concept of "essential use", which is considered to become a significant element in the future banning of MHC. In its communication "Guiding criteria and principles for the essential use concept in EU legislation dealing with chemicals" [15] published in 2024, the commission proposed a number of criteria for defining the "essential use". These criteria relate to their necessity of chemicals for human health or safety and their criticality for the functioning of society, especially if there exists no acceptable alternative. MHCs are defined on the basis of their hazard classifications (according to CLP regulation) and include all SVHCs as well as further SOCs. These criteria are summarised in Table 1.

*Table 1 - Summary of substance current and future categorisations by the EU. "☑" indicate effects/characteristics which can/would lead to a categorization. Categories (cat.) 1-4 indicate severity of a hazard from 1 being of highest severity. * Currently, substances leading to endocrine disruption for human health and the environment, to respiratory sensitisation or classified as 'specific target toxicity repeated exposure category 1' (STOT RE1) may be identified as SVHCs according to REACH Article 57(f) if considered of equivalent level of concern.*

Effect/Characteristic	SVHC [4]	MHC [3]	SOC [11]
Carcinogenicity	cat. 1A/1B	cat. 1A/1B	cat. 1A/B and 2
Mutagenicity	cat. 1A/1B	cat. 1A/1B	cat. 1A/B and 2

Toxicity for Reproduction	cat. 1A/1B	cat. 1A/1B	cat. 1A/B and 2
Persistent, Bioaccumulative, Toxic / very Persistent, very Bioaccumulative	☑	☑	☑
Persistent, Mobile, Toxic / very Persistent, very Mobile	☑	☑	☑
Endocrine Disruption for Human Health	*	cat. 1	cat. 1 and 2
Endocrine Disruption for the Environment	*	cat. 1	cat. 1 and 2
Respiratory Sensitisation	*	cat. 1	cat. 1
Skin Sensitisation			cat. 1
Aquatic Chronic			cat. 1 to 4
Hazardous to the Ozone Layer			☑
Specific Target Organ Toxicity Repeated Exposition	*	cat. 1	cat. 1 and 2
Specific Target Organ Toxicity Single Exposition			cat. 1 and 2
POP-regulation (EU) 2019/1021			☑

The EU chemical legislation finder (EUCLEF) is a public tool provided by ECHA, which gives a comprehensive overview of regulatory obligations for a given substance. In cases where substances are prohibited or restricted (e.g. with certain limit values) established in European regulations, this is marked with red or orange flags.

3. Green chemistry as an answer to the global crisis in the field of chemicals

In their seminal monography “Green Chemistry: Theory and Practice”, first published in 1998, two American chemists, Paul Anastas and John Warner, proposed several “principles”, which should be naturally followed by all chemists when they design new chemicals, to ensure future safe and sustainable chemical production. This list of 12 principles has since then become a guiding concept for chemists, who consider the transition of chemistry to “safe and sustainable by design” an essential move necessary in the light of the above-mentioned triple planetary crisis. In essence, the 12 principles of green chemistry as formulated by Paul Anastas and John Warner read as follows [16]:

1. Prevent Waste
2. Atom Economy
3. Less Hazardous Synthesis
4. Design Benign Chemicals
5. Benign Solvents and Auxiliaries
6. Design for Energy Efficiency
7. Use of Renewable Feedstocks
8. Reduce Derivatives
9. Catalysis
10. Design for Degradation
11. Real-Time Analysis for Pollution Prevention
12. Inherently Benign Chemistry for Accident Prevention

These principles have been established with the intention to guide chemists in the design of ideal products and processes and have since then gained world-wide interest by academia, industry and governmental institutions. Further adaptations or alternatives for green engineering [17] and circular chemistry [18] should also be mentioned.

Keijer et al. [18] stated the 12 principles of circular chemistry, which offer a more holistic approach to sustainable chemistry by considering also the economic framework in which chemistry is used. The principles read as follows:

1. Collect and use waste
2. Maximize atom circulation
3. Optimize resource efficiency
4. Strive for energy persistence
5. Enhance process efficiency
6. No out-of-plant toxicity
7. Target optimal design
8. Assess sustainability
9. Apply ladder of circularity
10. Sell service, not product
11. Reject lock-in
12. Unify industry and provide coherent policy framework

The SSbD criteria by which chemicals can be rated as safe and sustainable over the whole life cycle, will provide an objective basis for the green transition of the chemicals sector. Thus, the SSbD assessment, as presently evolving in the EU, will be probably applied in future to evaluate the effectiveness of the implementation of green and sustainable chemistry by manufacturers of chemicals.

The transition of the chemical sector towards SSbD will require industry not only to further improve the energy efficiency of the processes and the use of green energy, but also a change from non-sustainable, mainly petrochemical, sources to sustainable raw materials, such as biomass or waste including CO_2. Substances, which are produced from sustainable sources and used as starting materials for the manufacturing of other chemicals are usually called green platform chemicals (GPC) in the chemical literature, leading back to the main subject of this work.

As the compilation, selection and assessment of green platform chemicals are the focus of the present work, the next section will discuss these substances and their sources in more detail.

4. Green platform chemicals and their feedstocks

Biorefineries

Green platform chemicals are produced from biological resources, including agricultural waste materials, in production plants, which in analogy to petrochemical refineries are called biorefineries. In a biorefinery biomass is used to produce chemicals, fuels, energy and/or plastics. The resources used include wood, marine biomass, agricultural residues, energy crops or organic waste. They can be processed biologically, chemically, or thermally to yield many different products. As these raw materials are renewable, biorefineries are considered as key elements for the transition to sustainable chemicals production. One of the key products and intermediates from biorefineries are platform chemicals, which usually have many uses, including as intermediates for the production of more complex chemicals.[19-21].

Platform Chemicals or Platform Molecules are a concept synonymous to base chemicals in petroleum refineries (ethylene, benzene-toluene-xylene BTX, propylene, C4-olefines), as higher-value added substances are derived from them. In the early 2000s researchers have gained interest in the topic especially after the publication of the US Department of Energy's (DOE) report "Top Value Added Chemicals from Biomass" [22]. The report aimed to identify the most important bio-based building block chemicals produced from sugar which can be converted into high-value chemicals and materials. The DOEs report defined the term "building block chemical" as "molecules with multiple functional groups that possess the potential to be transformed into new families of useful molecules" [22]. This work has been used as a reference point by many researchers using the term "platform chemicals", but a range of different terms are used for the concept of building block chemicals from biomass. Bozell and Peterson revisited the DOEs report in 2010 [23], defining the potential of a substance to act as a platform as being able to serve as a starting material and offering flexibility. A recent JRC report [24] from 2019 on the European market for bio-based chemicals defines platform chemicals as "chemical building blocks and starting materials in the manufacture of a broad range of products". The report excludes platform chemicals though, which are mainly used for other applications (e.g. methanol as fuel and polyhydroxyalkanoates as polymers) as they were analysing the different value chains from an economical point of view. Even though the above-mentioned definitions and descriptions of the nature of a platform chemical are not concrete, most researchers seem to agree that platform chemicals are a group of bio-based molecules being able to serve as intermediate in the value chain for different products. Based on that, this work includes all chemicals which are called "platform chemicals", "platform molecules" or "building block chemicals" in the literature in its survey, if renewable feedstocks are proposed for its production. The full list is shown in the results section grouped by number of functionalities, and short dossiers including the substances' identity, all the surveyed data from ECHA proposed feedstock and reaction pathways, recent literature, number of patents, number of articles and number of reactions found in SciFinder[25]. Details on the survey are found in chapter 5. A quick overview of the production process from biomass to platform chemicals is given in Figure 1.

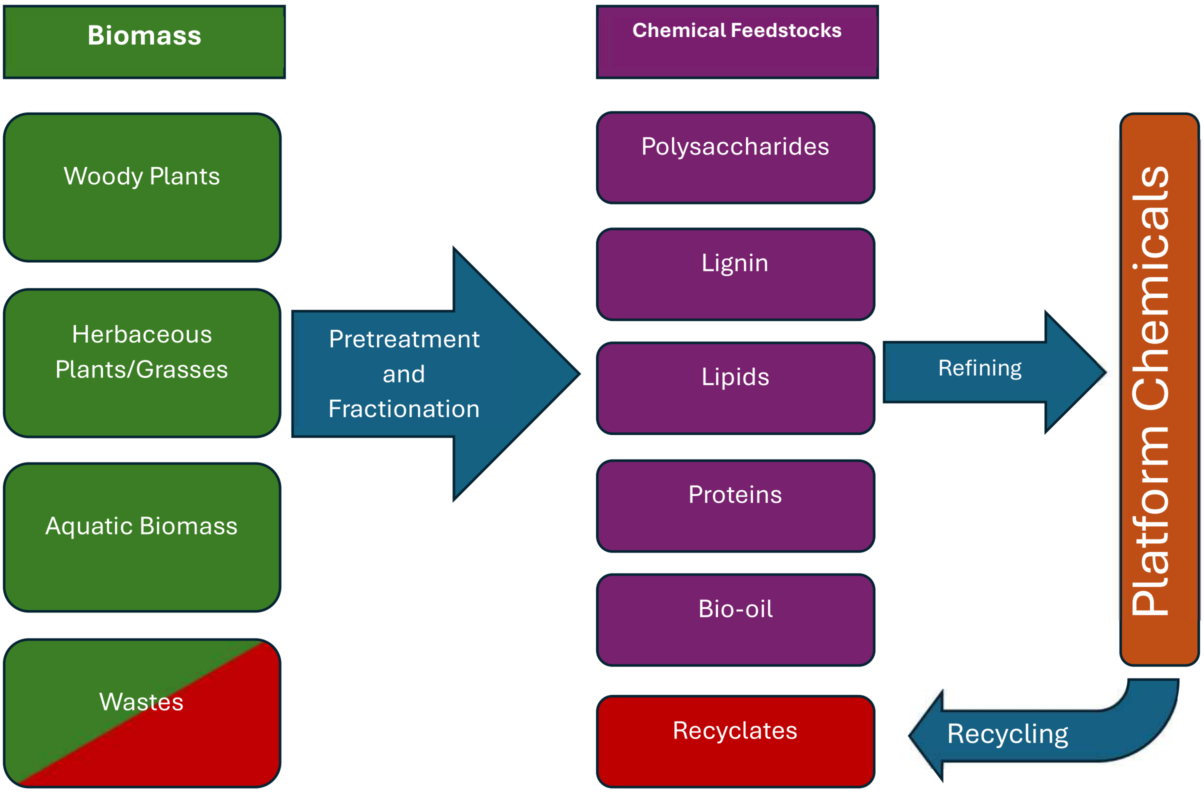


Figure 1 - General overview over the production process of platform chemicals from renewable feedstocks.

Biomass

In the beginning of the production process in a biorefinery there are different kinds of biomass feedstocks. Put in simple terms, biomass can be divided into woody plants, herbaceous plants/grasses, aquatic biomass, and wastes. Compared to petroleum, the feedstocks used in the biorefinery context have a higher content of heteroatoms (mainly oxygen), which make them in some cases more similar to the target compounds in chemical production [26]. The highest amount of carbon is captured by trees and marine plants [27]. The utilization of each kind calls for different pre-treatment and will be discussed in short before the main chemical feedstocks for platform chemicals. Interestingly enough, fungal biomass is rarely considered in the literature as feedstock for platform chemicals, but some species (white and red rot fungi) are proposed for processing of biomass [28, 29].

Woody plants

On land, the highest amount of carbon is captured by forests and herbaceous plants/grasses. Pan et al. estimated the global amount of forest biomass to be 861 billion tonnes of carbon [30] making it a major carbon sink and source for materials. The chemical composition of the produced lignocellulosic biomass varies from species to species, but in general, soft or hardwood are comprised of mostly cellulose (35-50 % dry weight), followed by lignin (20-30 % dry weight) and hemicelluloses (20-30 % dry weight). Compared to herbaceous plants and grasses, woody biomass grows slower over a longer period of time and yield more tightly bound materials [31].

Herbaceous plants/grasses

Herbaceous plants like sugar cane, sugar beets or corn, also contain lignocellulosic biomass but are mostly produced for their sugar and/or starch content. Oilseed plants is another major group within the herbaceous plants, the production of which is mainly focused on yielding triacyl glycerides for human consumption but also yields lignocellulosic biomass which can be utilized.

Perennial grasses such as white clover, alfalfa or legumes on the other hand can yield high amounts of protein but also cellulosic and soluble sugar fractions [32]. The global production according to the OECD-FAO Agricultural Outlook 2024-2033 for sugar cane was 1.9 billion tonnes, for sugar beets 262.8 million tonnes, for corn 1.2 billion tonnes and soya beans 400.3 million tonnes in 2023. These are all currently mainly used for food (high fructose corn syrup, oil, etc.) and feed, but biofuel production is also an important economically with ~20 % of sugarcane produced being transformed into bioethanol [33].

Aquatic Biomass

Often seen as a potential feedstock of the future, macro and microalgae and seagrasses have become the focus for many researchers, due to concerns of land use for other feedstocks based on competition with food production. According to the food and agricultural organization of the united nations (FAO), 35.1 million tonnes of algae biomass has been cultivated in 2022 [34]. Macroalgae (red, brown and green) are multicellular photosynthetic organisms, containing up to 27 % of their dry weight in protein and high amounts (up to 68 wt% dry matter) of soluble and insoluble fibre fractions [35]. Macroalgae can be cultivated close to the shoreline [36].

In contrast, microalgae are single cellular organisms with similar amounts of protein, significantly higher lipid content and lower amounts of polysaccharides than macroalgae [37, 38]. They are not only able to be grown in freshwater but also proposed to be cultivated in wastewater as treatment strategy [39-41].

Another important group of aquatic plants are seagrasses, which are considered a very important part of the nearshore habitats and highlighted for being a great carbon sink [42]. Like macroalgae, they are multicellular organisms growing under water, but as they are angiosperms, their cell walls contain cellulose, hemicellulose and lignin [43].

All three mentioned resources have been proposed as a feedstock for biofuel production, fermentable sugars, pharmaceuticals, nutraceuticals and food additives [44-50].

Wastes

As the United Nations Environment Programme estimated 1,052 million tonnes of food wasted globally in 2022 [51], it should be to no one’s surprise that the topic of waste utilization is a very important one. Municipal wastes (food scraps, lawn clippings, papers, etc.), agricultural wastes (livestock and poultry manure, agricultural crop residues), forestry residues (everything not marketable as wood including foliage, stumps, damaged trees, etc.) are commonly discussed carbon sources in context of biorefineries [27]. Two examples of utilizable waste streams for platform chemicals are dried distillers’ grain and solubles (DDGS) from bioethanol production and shrimp and crab shells from the seafood industry. The latter is a source of chitin which is used, after depolymerization to its monomer N-acetylglucosamine, in pharmaceuticals and cosmetics, with potential for the bio-based production of organonitrogen compounds [52]. DDGS is mainly used as cattle feed because of its high protein content, but could also be used for the production of chemicals [53].

A waste category not considered in the context of biorefinery, but necessary to be discussed in the transformation to a circular economy, is plastic waste. Since 1950 the production of plastics has increased to 370 million tonnes in 2019 [54]. Some researchers see pyrolysis as a suitable way of utilization of this waste since the obtained pyrolysis- and bio-oil can yield high value-added chemicals and fuels [55, 56].

Pre-Treatment and Fractionation

As the above discussed biomass categories are very diverse on their own, the pre-treatment methods to obtain their fractionated biochemical constituents represent a similarly divers and complex topic. The kind of pre-treatment used in a biorefinery process strongly influences which products can be efficiently obtained. For example, harsh conditions on cellulosic materials can degrade its polymeric structure strongly, rendering the technique unsuitable for the generation of strong fibres as targeted product. Also press cakes and meals of rapeseeds, soybeans or jatropha from biodiesel production could further be exploited for protein extractions [53]. Therefore, smart pre-treatment strategies can also help to utilize the full potential of all biochemical fractions [57].

The pre-treatment strategies for lignocellulosic biomass were developed mainly for the pulp and paper industry. The two main processes used are the Kraft- and the Sulphite-process. In the Kraft process, the lignocellulosic biomass is treated with aqueous solution containing sodium hydroxide and sodium sulphide. The lignin is solubilized by cleaving β-O-4 and α-O-4 linkages freeing hydroxyl groups to be ionized. The Sulphite-process uses a treatment with sulphites and bisulphites, cleaving β-O-4 and α-O-4 linkages and introducing polar groups to solubilize the lignin. Both processes yield high quality cellulose, but also lignin with sulphur introduced into its structure, which leads to numerous problems in the further depolymerization of lignin. Besides the sulphur addition, repolymerization via formation of C-C bonds is another challenge for further utilization [58]. The obtained lignin is mainly burned directly to recover energy for the energy intensive pulping and paper production processes [59].

The more novel processes developed also have the quality of lignin in mind. Organosolv processes use mixtures of organic solvents and water to solubilize lignin and separate it from the rest of the lignocellulosic biomass but degrading it less than technical lignin processes would. The solvents used in early methods were mainly ethanol, acetic acid or methanol, but newer methods using glycerol [60, 61], tetrahydrofuran [62, 63] or γ-valero lactone [64] and other alternatives [65-67] have since then been researched. Milled wood lignin (MWL) is obtained by extensive grinding of the biomass and extraction of the lignin with organic solvent/water mixtures [68-70]. Cellulolytic enzyme lignin (CEL) uses finely ground wood as base material and enzymatically cleaves some glycosidic bonds of cellulose and hemicellulose to yield lignin with a high molecular weight, which can be utilized for novel materials. The processes rate can be increased by combining it with mild acidolysis [70-72]. The utilization of ionic liquids [73-76] and deep eutectic solvents [77-80] have been suggested as well and investigated for the pre-treatment of lignocellulosic biomass.

Extraction of lipids from biomass starts by mechanical, chemical or biological disruption of the cell walls, often performed by pressing followed by solvent extraction [81]. The most common mechanical techniques currently used are bead beating and high-pressure homogenisation among others [82]. Since algae do not contain lignin, cell disruption of algal biomass can often be performed without energy intensive mechanical processes and use biological whole-cell or enzymatic methods directly instead [83]. Due to the more rigid cell walls of microalgae, many standard solvent extraction methods are not economically feasible, which led to the investigation of new techniques including super critical CO_2 and ionic liquids [84-86].

The simplest methods of separating proteins from biomass are acidic or basic extractions, which can lead to racemization and other modifications of amino acids [87]. Therefore, more sophisticated methods using enzymes [88], chemical-[89] or mechanical treatments [90, 91] have been developed [92]. The hydrolysis of the proteins to yield free amino acids can be achieved chemically with for example hydrochloric acid or sulfonic acid, but this runs the risk to lead to unwanted modifications and degradations [93]. Using a combination of different proteases can yield fully hydrolysed proteins as well as no degradation of the amino acids [94, 95]. Another method considered is sub critical water hydrolysis, utilizing the increased ionic product to catalyse the reaction [96, 97]. After hydrolysis, the mixture of amino acids needs to be separated, and the amino acids purified for further utilization. The amino acids can be fractionated by their different physicochemical properties. The different techniques investigated include reactive extractions [98, 99], selective adsorption to porous materials [100] or electrodialysis [101].

Pyrolysis as pre-treatment is considered as versatile as it accepts all of the above mentioned feedstocks and can yield low molecular weight products considered as platform chemicals [102]. The process thermally degrades organic molecules in anaerobic atmosphere to chemically complex mixtures of gases and oils as well as a solid fraction simply called biochar. The gases formed are mainly carbon monoxide, carbon dioxide, methane and other hydrocarbons. The liquid fraction, also known as bio-oil, contains an aqueous phase containing low molecular weight acids and alcohols (e.g. acetic acid, methanol) and a non-aqueous phase containing oxygenated compounds and aromatics [103]. Hydrothermal liquefaction uses subcritical or supercritical water to depolymerize biomass and yields similar oil fractions to those of pyrolysis [104].

Chemical Feedstocks

Polysaccharides

The most important feedstocks for the production of platform chemicals are carbohydrates. This is not only based on the abundance of carbohydrate sources such as cellulose and starch, but also on the development of metabolic engineering of microorganisms utilizing glucose as feed for many different products.

Glucose represents the monomer of two of the most abundant biopolymers, cellulose and starch, and has been utilized not only in fermentations but also in chemical processes. One of the most important sources for fermentable glucose are starch hydrolysates and raw sugar [105] since they are readily available from energy crops (e.g. corn). One of the major biomass cultivated for sugars by far is sugarcane, amounting to 1.9 billion tonnes produced worldwide in 2023, according to the OECD [33]. Sugarcane is pressed and the juice is clarified to yield sucrose syrup, which can be directly fermented to yield ethanol or further hydrolysed to glucose and fructose. For the USA, corn starch is the most important source for bio ethanol, leading to a production of around 14 billion gallons (~54 billion litres) of ethanol based of corn [106].
Starch is a biopolymer made up of amylose and amylopectin, based on α-1,4-glucose monomer units, with amylopectin being heavily branched via α-1,6 bonds. Its main sources vary geographically, but the main sources are corn, wheat, potato and rice plants. Historically, acid hydrolysis was the main production method of glucose from starch, but most modern production uses enzymatic processes [107].
To avoid the conflict between food vs. fuel (or other chemical commodities), researchers started to focus on lignocellulosic biomass, e.g. sugar cane bagasse, forestry residues, grasses [108-111] and waste streams [112-115] as a sugar source.
Cellulose, the most abundant of the three constituents of lignocellulosic biomass, is a biopolymer made up of β-1,4 bonded glucose units. Since it is not digestible by humans, it is a promising source for glucose for fermentations and chemical transformations. In nature cellulose is found embedded into a matrix of hemicellulose and lignin which gives plants their

strength but also complicates the valorisation. The recalcitrance of cellulose is furthermore increased by its high crystallinity and its strong intra- and intermolecular bonds. The hydrolysis of cellulose into glucose can be easily performed by using mineral acids, for example sulphuric acid or phosphoric acid. As those are not sustainable methods, because of their bad recyclability and corrosiveness just to name a few aspects, research on alternatives has been performed extensively. Solid catalysts such as metal oxides, zeolites, acid resins, etc. are being developed as they offer easy recyclability and separation [116-123]. Ionic liquids are also considered as solvents and Brønsted acid catalysts for hydrolysis of cellulose in homo- and heterogeneous processes [124-128]. The chemo catalytic pathways from glucose to platform chemicals [129-132] as well as direct production from cellulose [129, 133-138] are both being researched intensively.

Another saccharide discussed in research is xylose, the main pentoses found in hemicellulose. As it is found in major amounts in corn stover hydrolysate, utilizing it would be of ample importance [139]. The first process for the production of one of the main target platform chemical furfural has been developed by Quaker Oats in 1921, using sulphuric acid at elevated temperatures to dehydrate xylose [140]. Similar processes are still used to produce furfural nowadays [141] and research focuses on greener catalysts, dehydrating xylose [142-146] or xylan rich biomass [147-149]. Fermentative methods have not been utilized as much as for glucose and other hexoses found in hemicellulose, due to most microorganisms not being able to ferment xylose with high efficiency [150]; in addition, lignocellulosic hydrolysates contain high amounts of glucose, which inhibits the uptake of xylose into most microorganisms [151]. A lot of research is still being conducted, since it is the second most abundant sugar derived from lignocellulose, yielding ethanol [152, 153], ethylene glycol [154], glutamic acid [155] and many other products [156-159].

Chitin is the most abundant nitrogen containing biopolymer made up from N-acetyl-D-glucosamine units. One of its main sources is the sea food industry producing around 8 million tonnes of waste crab, shrimp and lobster shells each year [160], but other sources such as fungi are also being researched [161, 162]. Based on its abundance and on containing nitrogen, chitin is a great feedstock for platform chemicals such as N-acetyl-glucosamine (GlcNAc) for the bio-based production of N-heterocycles, amino acids, amino sugars and amino alcohols [52, 163]. The extraction of chitin from shrimp waste is challenging because of the compact matrices of proteins and minerals in which it is interlaced. Demineralization and deproteinization is performed by acidic and basic treatment [164]. A common depolymerization method for chitin is acid hydrolysis using hydrochloric acid [165-167], but other chemical [168-171], enzymatic [172-177] and combined methods [178] have been explored in recent years.

Additional polysaccharides mentioned in research are fucoidan and carrageenan which could yield sulphur containing chemicals such as 2-methoxy-5-methyl-thiophene but also other platform chemicals [179-181]. These carbohydrates are found in brown and red algae, which are often referenced to be a future feedstock for biochemicals and biofuels [182], but research is mostly limited to direct applications in pharmaceuticals [183-186].

Lignin

As one of the three main constituents of lignocellulosic biomass, lignin has been extensively researched as feedstock for platform chemicals and for use as a polymer. It is an amorphous polymer based on mostly phenyl propenyl monomer units which are randomly linked by C-C and C-O bonds [187, 188]. It is the most abundant aromatic polymer with an estimated annual production of 5-36 hundred million tonnes per anno on earth [189]. Depending on the plant source, the structure and amount of lignin vary, but the most recurring moieties are β-O-4 linkages. The high complexity of the native polymer makes research into its utilization a challenging task.

Strategies for lignin depolymerization are as diverse as its structure. Oxidative methods using peroxides, peroxyacids or oxygen can be used under mild conditions and converting it into monomers with different alcohol, aldehyde and acid moieties [190-194]. Reductive methods mainly focus on the production of bio-oils [187, 195, 196], but monomeric phenol units can also be obtained [197-201]. Research into biochemical depolymerization of lignin from different sources by fungi [202-205], bacteria [206-209] and enzymes [210-212] is promising, but still lacks high productivity needed for industrial applications [213].

The valorisation of lignin, as one of the largest fractions of lignocellulosic biomass, could not only increase the feasibility of biorefineries, but also substitute many chemicals produced from oil and gas. The production of vanillin, a platform chemical, is already based in major parts on lignin [214], but also aromatic compounds such as benzene, toluene and xylene (BTX) could be produced from lignin [59, 215].

Lipids

Lipids as feedstock for platform chemicals are mainly produced from plant fats and oils in the bio diesel sector. In the context of platform chemicals, mainly terpenes and glycerol (as by-product of fatty acid esters production) are discussed, but also some fatty acids are considered as such. Because of the food and feed vs. fuel and land-use debates, research started to focus more on microalgae as biomass for lipid production.

The main coproduct of biodiesel production is glycerol (around a tenth of its volume), which is mentioned in many articles to be a promising platform chemical [22, 216-220]. According to the FAO agricultural outlook 2023, biodiesel production increases in the coming years and with it the production of glycerol [33].

Proteins

Besides producing amino acids by fermentation of sugars, some researchers have suggested to extract proteins from biomass [53, 221, 222]. Especially glutamic acid is of great interest as a good platform chemical, as it is not an essential amino acid and can be transformed into different bulk chemicals. Similar to lipids, the biomass explored for protein extraction includes microalgae [40], macroalgae, press cakes of oil plants [223], but also a variety of grasses and animal slaughter wastes [53]. The protein contents of these sources are already utilized for biogas production or animal feed, but some are not yet exploited. An investigation into the availability of grass in the EU by Meyer et al. [224] estimated the amount of excess grass in 2030 to be between 20 and 110 Mt. Another abundant source for protein extraction would be dried distillers' grain and solubles (DDGS), a by-product in bioethanol production from corn and maize, with 40 million tonnes available in the US in 2015 [225]. DDGS contains around 20-40 w/w% crude protein in its dry mass [225, 226]. Cultivating microalgae in swine wastewater has not only proven as effective treatment method, but also as possible protein source with a dry weight content of 40-50% [40, 41, 227]. To obtain the amino acids considered platform chemicals from proteins, acidic or basic hydrolysis can be performed as easy methods, but this can lead to racemization. Hydrolysis using proteases [88, 228, 229] or subcritical water techniques [96, 97, 230] have been proposed as greener alternatives.

Bio-oil

Bio-oil is a complex mixture of different substances produced by pyrolysis, the thermal decomposition of biomass under exclusion of oxygen, or hydrothermal liquefication in hot-compressed water. The possible products yielded from these processes depend strongly on the feedstock and the employed separation techniques. Products (some of which are considered platform chemicals) derived from cellulose fragmentation are glucoses dehydration product levoglucosan which undergoes different chemical transformation to yield furan, furfural, acetic acid, formaldehyde, glycolaldehyde and many more [231]. Lignin based bio-oil contains a number of different phenolic compounds considered as platform chemicals such as guaiacol, vanillin or phenol [232]. After degradation of the biomass, further fractionation into aqueous and organic phase of the bio-oil is necessary, which can be performed with many different methods [233]. Fractional condensation usually creates a light and a heavy fraction by leading the pyrolysis vapor through condensers with decreasing temperatures [234]. Another method to separate the different fractions are liquid-liquid extractions with water and different organic solvents or supercritical fluids [235-237].

5. Methodology of the present survey and preliminary assessment of green platform chemicals

The aim of this thesis was to identify GPCs from the literature, to list all selected substances, and to conduct a first, preliminary assessment of these substances. In this evaluation the substances are further characterised and evaluated by extracting specific information from ECHA's public database, focusing on substance identity, registration status, hazard classification, activities according to PACT, regulatory obligations besides REACH and based on their hazard classifications potential categorization as SVHC, MHC or SOC.

As already noted, there is currently no generally accepted formal definition of GPCs. This survey was thus conducted quite pragmatically by searching for the phrases "Green Platform Chemical", "Green Platform Molecule", "Platform Chemical", "Platform Molecule", "platform" and "building block" within SciFinders reference search engine. The literature found was checked for substances being called "platform chemical", "platform molecule" or "building block". As discussed above, platform chemicals are considered as green for this purpose only if the proposed production method is based on renewables. Most renewables considered in the existing literature are made from biomass, which is either specifically produced for its utilization or, even more frequently, agricultural waste. However, also other feedstocks such as industrial or household waste have been considered as renewables if they are described in the literature. Chemical isomers noted as such in the literature were explicitly stated as individual substances (e.g. as D-form or L-form) or considered as racemic mixture if the isomer was not specifically addressed. It is noted that since the proposed production methods in the literature lead to L-amino acids (be it by extraction of plant proteins or fermentation of sugars) and the D-isomers were not specifically mentioned, only the L-forms were surveyed.

Substances were considered as „Green Platform Chemicals" if the following criteria were fulfilled:

- Molecule was mentioned as
    - "Platform Chemical"
    - "Platform Molecule"
    - "Building Block"
- Has a proposed production route based of renewable feedstocks

The relevance of the identified platform chemicals was evaluated by searching for the number of patents and papers containing the substances name or its CAS number and reference to platform chemicals or synonymous concepts in SfiFinders reference search engine. The search term read as follows: "("Substance Name" OR "CAS No.") AND ("Platform Chemical" OR "Platform Molecule" OR "Building Block")". The number of reactions found when defined as reactant and reagent were also surveyed to describe the flexibility in chemical synthesis by entering the CAS Number into SciFinder and searching for reactions as reactants or reagents. SciFinder defines reactants as substances which add at least one carbon atom to the product, and reagents as substances adding at least one non-carbon atom to the product.

Subsequently, the substances on the list were searched in ECHAs public database using their respective CAS number. Chemical isomers were surveyed as explicitly stated within the literature or as racemic mixtures. Only data found within ECHAs database was used in the survey. The data taken includes the following:

- Substance identity providing other names, EC number, molecular formular, structural formular, type of substance, smiles notation, molecular weight,
- harmonised classification (carcinogenicity, mutagenicity, toxic for reproduction, other endpoints). These classifications have been adopted at European level and are listed in annex VI of the CLP regulation.
- notified classification (carcinogenicity, mutagenicity, toxic for reproduction, other endpoints, total number of notifiers, numbers of aggregated notifications). These classifications have been notified by companies, which place these substances as such or in mixtures on the market.
- registration status including tonnage band.
- information from PACT (public activities information tool) addressing status, latest update, competent authority. This information relates to the current regulatory activities on the substance.
- regulatory obligations indicating that the substance is restricted under REACH (Annex XVII) or subject to authorization under REACH (Annex XIV)
- other regulatory obligations like bans or restrictions as indicated in EUCLEF (indicated as correspondingly red flags or orange flags)

The listed platform chemicals have also been categorised as SVHC, MHC and/or SOC, based on the data on harmonised and notified hazard classification. Furthermore, the inclusion of the substances in the POP regulation [238] and the PMT/vPvM status on the basis of a report by the German environment agency [239] is indicated in the substance's information.

All the compiled data is made publicly available within the data repository of TU Wien for future research [240]. The gathered information is also summarised for each of the most relevant substances in the form of a short dossier in chapter 7. As "most relevant" were considered:

- highest reported production volume (over 10 million tonnes/year)
- Top 3 most patents reported
- Top 3 most references found on SciFinder
- Top 3 most reactions as reactant reported
- all the substances on the list of the DOEs report [22]

6. Results of the survey and assessment

The list of all surveyed platform chemicals names, CAS Number, highest prioritized functional group and SciFinder results are shown in Table 2 for monofunctional,

Table 3 for difunctional and Table 4 for polyfunctional molecules.

Table 2 - All monofunctional platform chemicals and their CAS-Number, highest prioritized functional group, number of results in SciFinder, number of patents in SciFinder and number of reactions as reactants listed in SciFInder.

Name	CAS-Number	Highest prioritized functional group	# Results	# Patents	# Reactions
1-pentanol	71-41-0	Alcohol	76	2	5189
1-propanol	71-23-8	Alcohol	189	12	12889
2-methyl-1-butanol	137-32-6	Alcohol	18	1	489
3-methyl-1-butanol	123-51-3	Alcohol	28	2	3264
acetaldehyde	75-07-0	Aldehyde	298	9	30984
acetic acid	64-19-7	Acid	1044	65	69042
acetone	67-64-1	Ketone	912	53	68486
butanol	71-43-2	Alcohol	372	25	23993
butyric acid	71-36-3	Acid	149	9	6248
butyrolactam	107-92-6	Amide	57	3	6155
caprolactam	616-45-5	Amide	33	4	6052
carbon monoxide	105-60-2		735	44	143744
carbon dioxide	77-92-9		2118	90	104168
ethanol	64-17-5	Alcohol	1767	80	105104
ethylene	74-85-1	Olefine	803	64	63285
ethylene oxide	75-21-8	Ether	130	7	20438
formic acid	64-18-6	Acid	469	17	57024
iso-butanol	78-92-2	Alcohol	128	11	3085
iso-propanol	67-63-0	Alcohol	520	20	31310
methanol	7512-17-6	Alcohol	3071	97	281144
propionic acid	106-42-3	Acid	229	12	9911
propylene	127-17-3	Olefine	273	20	22587
valerolactam	675-20-7	Amide	4	0	2410
γ-valerolactone	108-29-2	Ester	92	3	1167

Table 3 - All difunctional platform chemicals and their CAS-Number, highest prioritized functional group, number of results in SciFinder, number of patents in SciFinder and number of reactions as reactants listed in SciFInder.

Name	CAS-Number	Highest prioritized functional group	# Results in Scifinder	# Patents in Scifinder	# Reactions as Reactant
1,2-propanediol	57-55-6	Alcohol	105	25	9396
1,3-butadiene	106-99-0	Olefine	156	20	24058
1,3-diaminopropane	109-76-2	Amine	122	4	12853
1,3-propanediol	504-63-2	Alcohol	215	21	11740
1,4-butanediol	110-63-4	Alcohol	198	21	30265
1,4-cyclohexadiene	628-41-1	Olefine	26	1	1358
1,4-diaminobutane	110-60-1	Amine	120	10	7583
1,5-diaminopentane	462-94-2	Amine	61	1	3501
1,5-pentanediol	111-29-5	Alcohol	64	8	3700
2,3-butanediol	513-85-9	Alcohol	64	2	1369
3-hydroxybutyricacid	300-85-6	Acid	11	1	278
3-hydroxybutyrolactone	7331-52-4	Ester	16	2	158
3-hydroxy-propionic acid	503-66-2	Acid	3297	290	645
3-hydroxyvalerate	10237-77-1	Acid	14	0	36
4-aminobutyricacid	56-12-2	Acid	10	1	3250
4-hydroxybutyricacid	591-81-1	Acid	4	0	197
5-aminovalericacid	660-88-8	Acid	4	0	900
5-hydroxyvalericacid	13392-69-3	Acid	4	0	100
6-aminocaproicacid	60-32-2	Acid	8	1	3599
acetoin	513-86-0	Ketone	37	0	928
acrylic Acid	79-10-7	Acid	267	58	97036
adipic Acid	124-04-9	Acid	139	22	19981
d-limonene	124-38-9	Olefine	47	0	1270
ethylene glycol	107-21-1	Alcohol	770	60	62273
glutaric acid	110-94-1	Acid	57	12	2429
glycine	56-40-6	Acid	659	33	16925
glycolaldehyde	141-46-8	Aldehyde	49	3	1136
glycolic acid	79-14-1	Acid	85	4	5822
isoprene	78-79-5	Olefine	112	5	14428
lactic acid	50-21-5	Acid	386	12	4449
l-alanine	498-07-7	Acid	510	13	8161
levulinic acid	5989-27-5	Acid	449	22	6433
l-proline	56-87-1	Acid	460	14	1240
malonicacid	67-56-1	Acid	37	3	17336
oleic acid	108-95-2	Acid	372	15	7567
oxalic acid	108-73-6	Acid	168	19	13708
pyruvic acid	56-45-1	Acid	166	6	5771
succinic acid	134-96-3	Acid	307	26	9692

Name	CAS-Number	Highest prioritized functional group	# Results in Scifinder	# Patents in Scifinder	# Reactions as Reactant
undecylenic acid	112-38-9	Acid	48	2	2005
α-angelica lactone	591-12-8	Ester	11	0	1648
β-angelica lactone	591-11-7	Ester	4	0	107
γ-aminobutyric acid	56-12-2	Acid	107	8	3250
γ-angelica lactone	10008-73-8	Ester	9	0	119

Table 4 - All polyfunctional platform chemicals and their CAS-Number, highest prioritized functional group, number of results in SciFinder, number of patents in SciFinder and number of reactions as reactants listed in SciFinder.

Name	CAS-Number	Highest prioritized functional group	# Results in Scifinder	# Patents in Scifinder	# Results as Reactant
1,4-benzoquinone	106-51-4	Ketone	128	5	9978
2,5-furandicarboxylic acid	3238-40-2	Acid	162	7	2288
2-methoxy-5-methyl-thiophene	31053-55-1	Thioether	0	0	11
2-propylphenol	644-35-9	Alcohol	3	0	194
3-acetamido-5-acetylfuran	95598-28-0	Amide	6	0	79
3-propylphenol	621-27-2	Alcohol	0	0	47
4-propylphenol	645-56-7	Alcohol	16	0	481
5-chloromethylfurfural	1623-88-7	Aldehyde	20	1	533
6-amyl-2-pyrone	27593-23-3	Ester	18	0	17
aconitic acid	499-12-7	Acid	12	0	153
anthranilic acid	56-41-7	Acid	2471	249	14579
arabitol	118-92-3	Alcohol	15	2	24
ascorbic acid	2152-56-9	Ester	171	9	1791
aspartic acid	50-81-7	Acid	346	17	3425
benzene	56-84-8	Olefine	860	55	27632
catechol	630-08-0	Alcohol	252	7	9109
citric acid	120-80-9	Acid	287	48	5320
erythritol	149-32-6	Alcohol	56	5	645
eugenol	97-53-0	Ether	65	4	2809
farnesene	502-61-4	Olefine	12	0	122
ferulic acid	1135-24-6	Acid	62	4	2509
fructose	57-48-7	Ketone	287	10	3941
fumaric acid	110-17-8	Acid	149	21	14012
furfural	98-01-1	Aldehyde	645	9	34756
glucaric acid	25525-21-7	Acid	21	1	43
gluconic acid	526-95-4	Acid	34	1	288
glucosamine	3416-24-8	Aldehyde	158	8	616

Name	CAS-Number	Highest prioritized functional group	# Results in Scifinder	# Patents in Scifinder	# Results as Reactant
glutaconic acid	1724-02-3	Acid	2	1	112
glutamic acid	617-65-2	Acid	386	13	416
glycerol	56-81-5	Alcohol	557	48	20835
glycerol carbonate	931-40-8	Ester	35	3	890
guaiacol	90-05-1	Ether	137	3	5398
Hydroxymethylfurfural	67-47-0	Aldehyde	488	4	5886
isosorbide	652-67-5	Ether	96	8	4384
itaconic acid	97-65-4	Acid	130	12	7707
kojic acid	501-30-4	Ketone	4	0	2127
levoglucosan	37112-31-5	Ether	39	2	278
levoglucosenone	123-76-2	Ketone	14	0	554
l-serine	6915-15-7	Acid	494	18	4398
l-threonine	141-82-2	Acid	349	17	141
lysine	87-78-5	Acid	500	25	3561
malic acid	108-39-4	Acid	109	6	1492
mannitol	505-70-4	Alcohol	72	4	57
m-Cresol	123-35-3	Alcohol	57	1	5960
muconic Acid	95-48-7	Acid	16	1	91
myrcene	112-80-1	Olefine	36	0	2002
N-acetylglucosamine	144-62-7	Amide	157	9	1380
o-cresol	106-44-5	Alcohol	77	4	6818
p-cresol	99-96-7	Alcohol	112	1	12584
phenol	2628-17-3	Alcohol	899	44	56664
phloroglucinol	609-36-9	Alcohol	97	5	5696
p-hydroxybenzoic acid	79-09-4	Acid	77	2	8897
p-hydroxystyrene	115-07-1	Alcohol	21	2	3775
p-xylene	108-46-3	Olefine	110	3	6658
resorcinol	50-70-4	Alcohol	130	7	16336
sorbitol	100-42-5	Alcohol	87	8	2746
styrene	110-15-6	Olefine	872	90	152930
syringaldehyde	91-10-1	Aldehyde	36	0	2414
syringol	80-68-2	Ether	68	3	1332
toluene	108-88-3	Olefine	958	43	22577
vanilic acid	121-34-6	Acid	2446	248	1017
vanillin	121-33-5	Aldehyde	202	9	18460
xylitol	87-99-0	Alcohol	44	3	782
xylonic Acid	17828-56-7	Acid	7	0	5

The final surveyed list contains 131 entries of which 124 were found in ECHA's public database. As shown in Figure 1, 63 platform chemicals have a full registration and 24 a full and intermediate registration. 6 of the substances registered as intermediates have no full registration. For 31 substances only an entry into the C&L inventory was found in the database but they were not registered. The volumes of substances with a full registration by manufacturers in the EU are summarised in Table 5and shown in Figure 2.

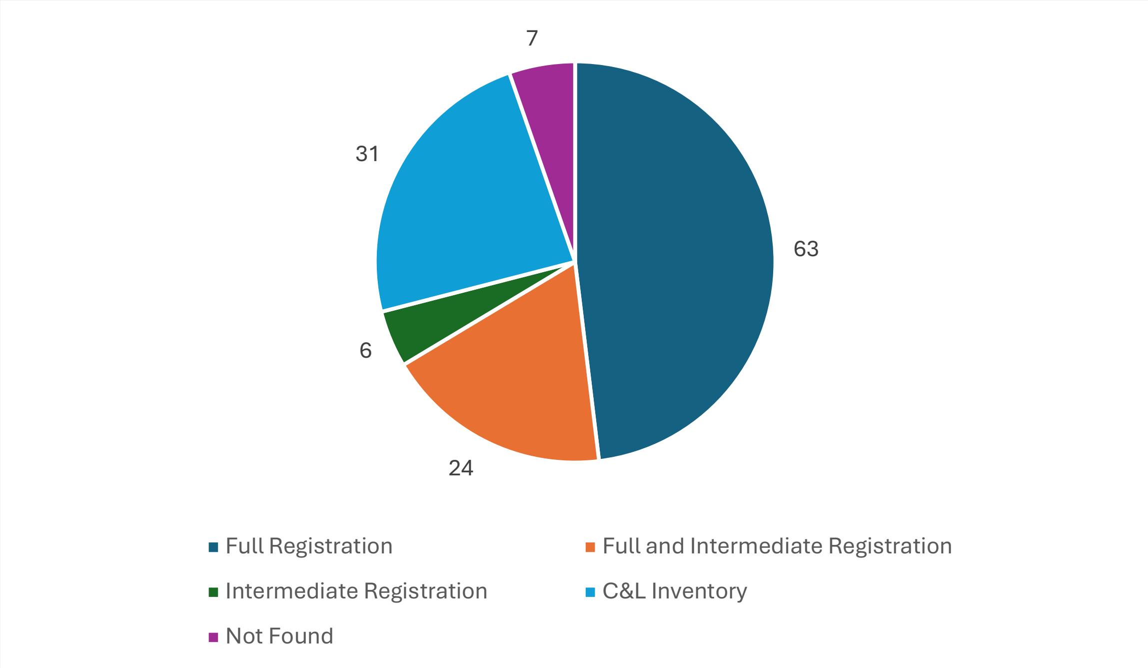


Figure 2 - Registration status of the surveyed platform chemicals

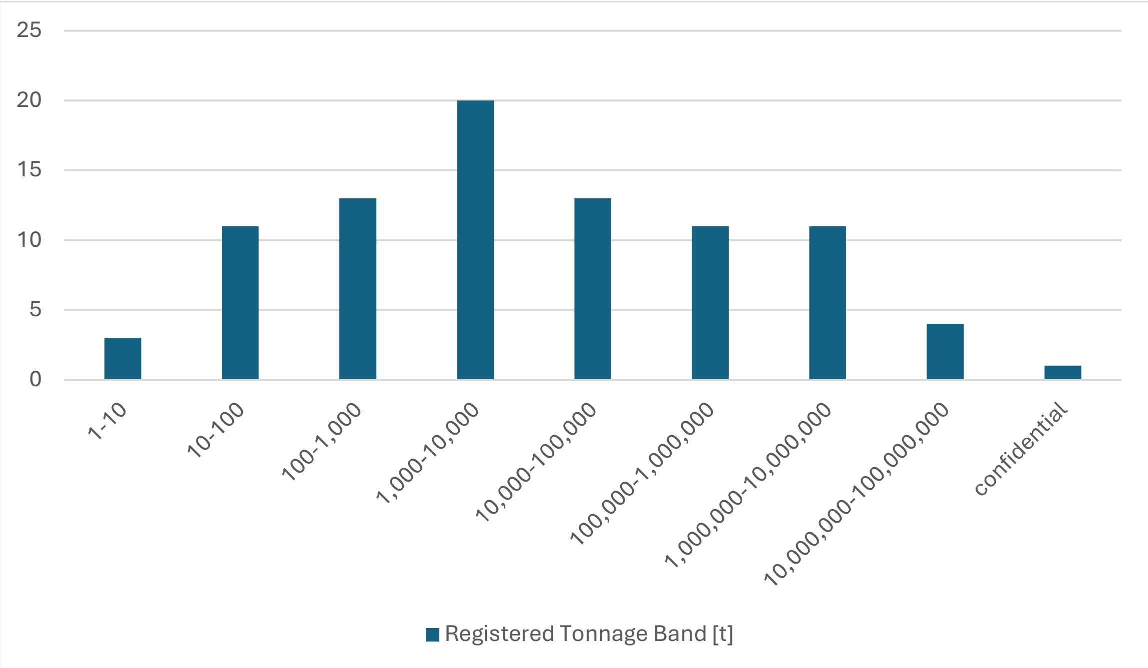


Figure 3 - Sum of platform chemicals with full registration reported in each tonnage band

Table 5 - Number of platform chemicals in each tonnage band

Tonnage band [t]	Number of substances within tonnage band
1-10	3
10-100	11
100-1,000	13
1,000-10,000	20
10,000-100,000	13
100,000-1,000,000	11
1,000,000-10,000,000	11
10,000,000-100,000,000	4
confidential	1

A summary of the harmonised classifications for all surveyed platform chemicals is given in Table 6. 11 substances are classified as CMR in at least one category. No platform chemical was found on the candidate list, but based on the harmonised classifications, 7 substances could be identified as SVHC in the future. 8 substances (including SVHCs) fall under the definition of MHC and 14 (including SVHCs and MHCs) of SOC based on their hazard classifications.

Table 6 - Summary of number and type of harmonised hazard classification of surveyed substances.

Harmonised classifications (hazard classes)							
Carcinogenic		**Mutagenic**		**Toxic for reproduction**		**Only other endpoints**	**Total number of substances with harmonised classifications**
Cat. 1	**Cat. 2**	**Cat. 1**	**Cat. 2**	**Cat. 1**	**Cat. 2**		
6	**1**	**3**	**4**	**2**	**2**	**30**	**41**

A summary of the notified classifications for all surveyed platform chemicals without harmonised classification is given in Table 7. For 18 substances, there are notified classifications which could lead to identification as SVHC in the future. The classifications would possibly be a reason for 30 substances to be identified as MHC and 65 as SOC.

Table 7 - Summary of number and type of notified hazard classification of surveyed substances.

Notified classifications (hazard classes)				
Carcinogenic	**Mutagenic**	**Toxic for Reproduction**	**Only other endpoints**	**Total number of substances with notified classifications**
4	**5**	**7**	**73**	**83**

The number of substances with ongoing or concluded processes under REACH and/or CLP according to PACT are summarised in Table 8.

Table 8 – Processes (ongoing or concluded) under REACH/CLP reported in PACT (summary of total 131 substances surveyed).

DEV	**SEV**	**CLH**	**SVHC**	**Recom**	**Restriction**	**ED**	**PBT**	**ARN**	**No activities**
55	13	14	1	0	1	3	0	33	64

Based on other EU-legislation (besides REACH and CLP), 11 substances are marked in EUCLEF with “red flags” indicating a ban and 65 with “orange flags” indicating a restriction (e.g. a limit value).

Only 7 of the 131 surveyed substances were not registered under REACH. These were 5-hydroxyvaleric acid (CAS: 13392-69-3), arabitol (CAS: 2152-56-9), xylonic acid (CAS: 17828-56-7), 3-acetoamido-5-acetylfuran (CAS: 95598-28-0), 2-methoxy-5-methyl-thiophene (CAS: 31053-55-1), muconic acid (CAS: 505-70-4) and glutaconic acid (CAS: 1724-02-3).

7. Discussion

7.1. Platform chemicals state and potential

General

On the final list of 131 platform chemicals there are many substances which are already produced in bulk within the EU. This includes some of the DOEs original report [22] on value-added chemicals: succinic acid (≥10 kt/a), fumaric acid (≥10kt/a), malic acid (≥10kt/a), 2,5-furandicarboxylic acid (≥10t/a), aspartic acid (≥1kt/a), glutamic acid (≥100t/a), itaconic acid (≥10kt/a), levulinic acid (≥100t/a), glycerol (≥1kt/a) and xylitol (≥1kt/a). 3-Hydroxybutyrolactone has a full registration under REACH, but the amount produced is reported as confidential. 3-Hydroxypropionic acid, glucaric acid, and sorbitol have all not been registered within the EU. Four platform chemicals of the compiled list have reported production volumes of more than 10 million tonnes, ethanol, ethylene, methanol and propylene. The share of ethanol produced from biomass is 93 % according to a market analysis by Jain et al. [241]. Ethylene, propylene and methanol are produced from biomass to some extent globally [242, 243]. Other examples already produced from biomass in bulk are levulinic acid produced by Maine BioProducts and Avantium [244] and vanillin produced by Borregard [214]. Data on the share of platform chemicals produced from renewable resources are not available within the registration database, but estimates in the JRC report "Insight into the European market for bio-based chemicals" report a share of 0.3% [24]. This number includes some proposed platform chemicals with very high production volumes such as ethylene of which 0% are produced of biomass within the EU; in contrast, lactic acid and 1,3-propanediol both have a 100% share of bio-based production within the EU. Globally, a report on bio-based chemicals by the IEA Bioenergy from 2020 [245] indicates many companies with potential growth in bio-based production. In their strength-weaknesses-opportunities-threats analysis for biorefineries, the volatility in fossil fuel prices, the availability of renewable feedstocks and high investment costs are some of the threats they are facing. A position paper written by DECHEMA commissioned by CEFIC [246] sees feedstock and renewable energy availability as the main challenges for the bio-based transition of the industry as well.

Based on the assessment of the technological readiness level of 25 sugar platform products by Taylor et al. in 2015 [247], most of the examined substances production pathways are based of biological methods. As most of the chemicals proposed sustainable production pathways via lignocellulosic biomass (respectively glucose from LC biomass) fermentation, developments tackling technical barriers in biomass pre-treatment and fractionation, as well as in downstream processing of fermentations are very important for the bio-based sector. Kim et al. also mention the need for improvement in downstream processing and pretreatment of biomass in a review on platform chemicals produced from metabolically engineered microorganisms from 2023 [248].

Besides the production of vanillin, the lignin fraction of biomass remains heavily underutilized for the production of platform chemicals. Integration of lignin valorisation by depolymerization could strongly increase the economic viability of biorefineries and therefore the production of platform chemicals from biomass [249]. Understanding the heterogeneous and complex structure and their changes in fractionation processes is still a challenging task. Avoiding condensation during the thermochemical depolymerization is another challenge to be tackled [57, 250]. Biotechnological approaches in depolymerization and modification of lignin still suffer from slow reaction rates, but could become a more feasible alternative with the advances in genetic engineering [251]. Sun et al. suggested in a review on catalytic lignin depolymerization that instead of focusing on producing the chemicals we already use (like BTX) from lignin, we should find ways of utilizing the chemicals we can already obtain in good yields [187].

Macro- and microalgae biomass is still underutilized as most of the research is still based on laboratory scale and focusing on bioethanol production only [252]. The advantages of high growth rate, absence of lignin and its cultivation not requiring fertile land underscore the high potential of the utilization of macroalgae [253].

In the 12 principles of green chemistry, it is stated that production of waste should be avoided [16] and Keijer et al. argue in their 12 principles of circular chemistry, that waste is a resource and should be collected and used as it is not possible to reduce all waste to zero [18]. There is already a lot of research performed on utilization of biological wastes such as food waste (potato peels [113], crustacean shells [254], general food waste [96]), forestry residues and agricultural wastes within the context of platform chemicals and biorefineries. Plastic waste, as it is not a form of biomass, might not fit into the biorefinery context, but its reduction and utilization are of utmost importance to achieve sustainability. As of 2015 6300 Mt of plastic waste has been generated globally of which 60 % was discarded in landfills and only 9 % had been recycled [255]. A review by Zhang et al. from 2024 compares and discusses research articles on life-cycle analysis of chemical recycling, which means pyrolysis or depolymerization by other means, of plastic wastes and concluded, that chemical recycling performs better than incineration, especially when there is a high amount of renewable energy used [256]. Research is conducted on co-pyrolysis of plastic waste and biomass which could improve pyrolysis processes also for biomass with potential for large-scale production of bio-oil, ultimately to be upgraded to platform chemicals [257]. Overall, the goal should be to reduce the waste to near zero by designing chemicals, processes and products accordingly, but the challenge of returning existing waste into the production cycle cannot be ignored.

As discussing all surveyed GPC in detail would be beyond the scope of this work, the most relevant or interesting have been picked to be discussed. This includes the 4 substances with a yearly production of more than 10 million tonnes (methanol, ethanol, ethylene and propylene), as well as the top 3 substances in patents (3-hydroxypropionic acid, anthranilic acid and vanillic acid), journal articles (3-hydroxypropionic acid, methanol and anthranilic acid) and reactions as reactant (methanol, styrene and carbon monoxide) according to hit numbers received in SciFinder. Since the original report by the DOE about bio-based building blocks has such a high relevance within the field, the final top 13 substances are discussed as well. The substances dossiers give a short overview of the results surveyed by this work.

Functional groups of proposed platform chemicals

The final list contains 131 molecules, which considering the lack of a formal definition of the term platform chemical is less than one might expect. The functionalities of the substances are mostly alcohols (66 substances), double bonds (54 substances), and acids (50 substances). 17 substances have nitrogen functionalities; one includes chlorine and another one a thioether. Around 18 % of the so-called platform chemicals only contain one, 33 % two and 49 % more than two functional groups. According to the often referenced DOEs report, the monofunctional substances would be excluded by the definition of building block chemicals [22]. This is especially interesting since ethylene for example is a key intermediate within the petrochemical production which could be produced from renewable resources and act as a drop-in substitute in already existing processes [258, 259]. Consequently, this exclusion should be critically reflected in future strategic concepts.

Number of reactions as reactant

Nevertheless, many of the small and monofunctional platform chemicals are of high interest to academia with nearly all but one having more than 1000 published reactions using them as reactant in SciFinders search engine. The di- and polyfunctional molecules have on average less reactions reported than the monofunctional substances. As one would expect and is shown in Figure 4, the number of reactions as reactant are high for molecules with a small number of carbon atoms making those arguably more versatile building blocks in chemical synthesis.

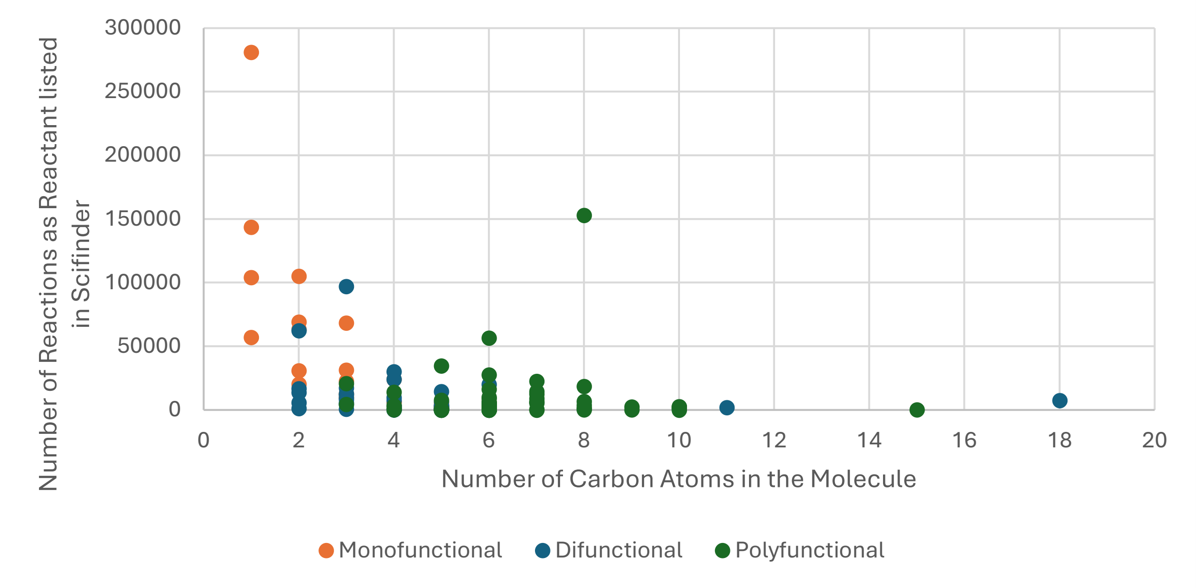


Figure 4 - Number of reactions as reactant of each surveyed platform molecule vs. the number of carbon atoms within the molecule.

The highest number of reactions as reactants were reported for methanol (281144), styrene (152930) and carbon monoxide (143744).

Number of results

The number of search results for each platform chemical can be used to estimate the interest of researchers into single molecules in the given context. This is by far not a representative method to evaluate the absolute interest of researchers, but it can show at least a trend. By the results of this evaluation, 3-hydroxypropionic acid (3297 results), methanol (3071 results) and anthranilic acid (2471 results) are the substances of highest interest. The average of results for all surveyed platform chemicals was 301 hits.

Number of patents

The number of patents for each substance in the context of platform chemicals range from 0 to low hundreds, indicating that not for all substances proposed as such research was fruitful enough to patent production processes. The number of patents resemble a preliminary evaluation of a platform chemicals progress in its development as such. Similar to the number of hits for journal articles, the content of the patents has not been further screened, and some might have been excluded for not including one of the platform chemicals related keywords. The most patents have been reported for 3-hydroxypropionic acid (290), Anthranilic Acid (249), and Vanillic Acid (248) but on average only 19 results were found.

The most relevant green platform chemicals

As mentioned above, short dossiers for the most relevant GPCs have been compiled. They include all the information surveyed from ECHA's public database (substance identity, harmonised and notified classifications, registration, entries in the public activity tool and other regulatory obligations besides REACH), as well as proposed feedstocks and production pathways, and information on their relevance in the literature (based on number of patents, number of references found on SciFinder, and number of reactions found on SciFinder). The criteria for inclusion in the list of the most relevant substances were:

- highest registered production/import volume (over 10 million tonnes/year)
- Top 3 most patents reported
- Top 3 most references found on SciFinder
- Top 3 most reactions as reactant reported
- all the substances on the list of the DOEs report.

The criteria leading to an inclusion are written in red and are underlined in the dossier. The substances for which dossiers have been arranged and their inclusion criteria are summarised in Table 1:

Table 9 - List of the most relevant substances dossiers. Criteria for inclusion are marked with ☑ for each substance.

Substance	**Inclusion Criteria**				
	Registered Volume	**Most Patents**	**Most References**	**Most Reactions**	**DOE Report**
Methanol	☑		☑	☑	
Styrene				☑	
Carbon monoxide				☑	
3-Hydroxypropionic acid		☑	☑		
Anthranilic acid		☑	☑		
Vanillic acid		☑			
Ethanol	☑				
Ethylene	☑				
Propylene	☑				
Succinic acid					☑
Fumaric acid					☑
2,5-Furandicarboxylic acid					☑
Aspartic acid					☑
Glutamic acid					☑
Itaconic acid					☑
Levulinic acid					☑
Glycerol					☑
Xylitol					☑
(S)-3-Hydroxybutyrolactone					☑
Glucaric acid					☑
Sorbitol					☑

Each dossier is followed by a short summary of each substances current production, proposed bio-based production pathway, (potential) uses and possible categorization as SVHC, MHC or SOC. Information on the current bio-based share production volume was included if numbers were available.

Methanol

Substance Identity
IUPAC-Name: Methanol
CAS No.: 67-65-1
Mass: 32.04 g mol $^{-1}$
Molecular formula: CH_4O

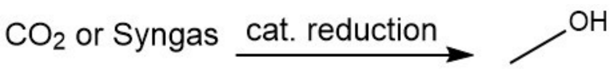
Classifications:
Harmonised: Flam. Liq. 2, Acute Tox. 3 *, Acute Tox. 3 *, Acute Tox. 3 *, STOT SE 1
Notified: Carc. 2, Repr. 1B, Repr. 2, Acute Tox. 2, Acute Tox. 3, Acute Tox. 4, Aquatic Acute 1, Aquatic Chronic 1, Aquatic Chronic 3, Eye Dam. 1, Eye Irrit. 2, Flam. Liq. 2, Not Classified, Skin Corr. 1A, Skin Corr. 2, STOT RE 1, STOT RE 2, STOT SE 1, STOT SE 2, STOT SE 3

Registration: 10 000 000 – 100 000 000 t/a

PACT: DEV 1-8: Concluded, Nov 2022; SEV: Concluded, Mär 20202, Poland; CLH: Opinion Adopted, Apr 2019, Italy; Restriction 1: Commission, decided; Restriction 2: Not conforming; ARN: Denmark, None

Regulatory Obligations (beside REACH/CLP):
Red Flags: -
Orange Flags: Cosmetic Products Regulation, Food Contact Recycled Plastic Materials and Articles Regulation-repealed, Inland Transport of Dangerous Goods Directive, Plastic Materials and Articles Regulation, Protection of Pregnant and Breastfeeding Workers Directive, Protection of Young People Directive, Recycled Plastic Food Contact Materials

Feedstock: CO_2 or Syngas
Production (most relevant):



Relevance:

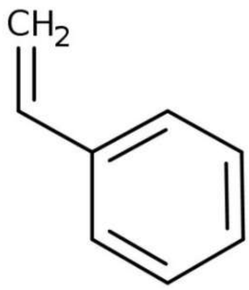
Patents: 97

Book/Review: Sustainable methanol production from carbon dioxide: advances, challenges, and future prospects, Patil et al., 2024, DOI: 10.1007/s11356-024-34139-3 [260]

Sci Finder References: 3071
Sci Finder Reactions: Reactant: 281144; Reagent: 236162

Methanol, as the simplest alcohol, is produced in a range of 10 to 100 million tonnes per year in the EU, has many possible applications in production of other chemicals and as alternative fuel [261]. Therefore, the number of reactions as reactant (281144), number of journal articles (3017) and number of patents (97) reported are of no surprise as it is commonly used in esterification of acids, as ligand in metal complexes and in transesterification. Its bio-based production can be achieved from biomass-based syngas ($CO + H_2$) or by reduction of CO_2 and is the possible starting point for the synthesis of bio-based olefins through the methanol-to-olefines (MTO) process [262, 263]. The MTO process uses ZSM-5 or SAPO-34 catalysts to transform methanol via dimethyl ether to olefines of different chain lengths [264, 265]. The production of methanol from syngas has been industrially performed for many years utilizing copper-zinc-alumina catalysts at elevated temperatures and pressure, but not of a bio-based source. Biomass for the syngas production is cheap, but has a high moisture and ash content which can lead to further problems in downstream processing as by-products might poison the catalysts [266]. The reduction of CO_2 is a promising route, as it directly binds one of the major greenhouse gases in either our atmosphere or effluent gases of industrial plants. There has been a lot of research on the topic including photocatalytic, electrocatalytic and thermo-catalytic methods. Tongxin et al. [267] summarise the progress of the development of photocatalytic reduction of CO_2 to methanol in a review and conclude the technique to be very promising but far away from industrial scale. Direct and indirect electro-catalytical CO_2 reduction still has challenges for its industrial use, such as the capture and storage of the CO_2 and catalyst stability [268]. Thermo-chemical production from CO_2 and H_2 is a more promising technology in carbon capture and utilization but is also energy intensive and has potential risks to be considered in each production step [269]. Sustainable methanol has been proposed to be used in methanol-to-olefins (MTO) processes [270] or for different products from microorganisms [271, 272]. Renewably produced methanol accounts currently for 0,2 % of all methanol production [273], but many companies are already involved [274]. As promising as methanol as a GPC based of renewable resources sounds, it is, based on the criteria laid down in the eco-design regulation and its harmonised classifications, a potential SOC which makes it a potential candidate for substitution in the future. Based on notified Classifications (Repr. 1B), it fulfils the definition and could therefore be categorised as SVHC in the future.

Styrene



Substance Identity

IUPAC-Name: Styrene
CAS No.: 100-42-5
Mass: 104,15 g mol $^{-1}$
Molecular Formula: C_8H_8

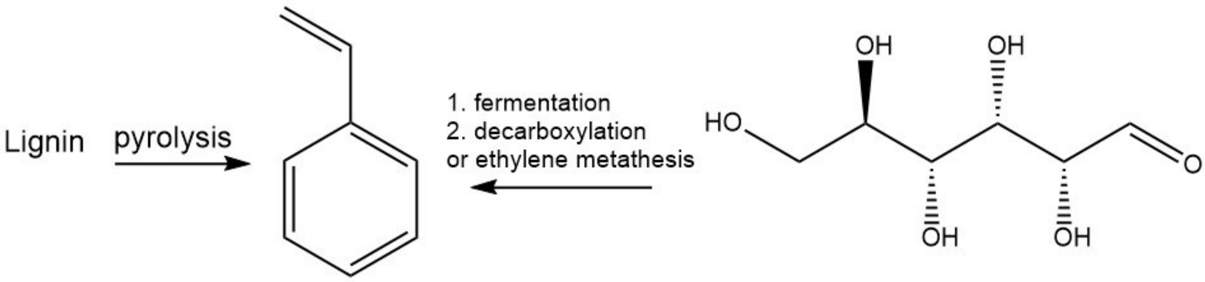
Classifications:
Harmonised: Repr. 2, Flam. Liq. 3, Skin Irrit. 2, Eye Irrit. 2, Acute Tox. 4 *, STOT RE 1
Notified: Carc. 2, Muta. 2, Repr. 1B, Repr. 2, Acute Tox. 3, Acute Tox. 4, Aquatic Chronic 3, Asp. Tox.1, Eye Irrit. 2, Eye Irrit. 2A, Flam. Liq. 3, Not Classified, Skin Irrit. 2, STOT RE 1, STOT SE 1, STOT SE 3

Registration: 1 000 000 – 10 000 000 t/a

PACT: DEV 1: Under Assessment, Jul 2023; DEV 2: Under Assessment, Mai 2023; DEV 3: Concluded, Nov 2022; DEV 4: Concluded, Nov 2022; CLH 1: Intention, Jul 2023, Netherlands, CLH 2: Opinion Adopted, Apr 2019, Denmark; ARN 1: na, Pending Action, GMT 301; ARN 2: CLH SVHC Other, ec 202-852-5; ARN 3: Denmark, No suggestion yet, na

Regulatory Obligations (beside REACH/CLP):
Red Flags: Cosmetic Products Regulation
Orange Flags: Food Contact Recycled Plastic Materials and Articles Regulation-repealed, Inland Transport of Dangerous Goods Directive, Plastic Materials and Articles Regulation, Protection of Pregnant and Breastfeeding Workers Directive, Protection of Young People Directive, Recycled Plastic Food Contact Materials

Feedstock: Lignin (via Pyrolysis), Glucose (via Cinnamic Acid)
Production:



Relevance:

Patents: 90

Book/Review: -

Sci Finder References: 872
Sci Finder Reactions: Reactant: 152930; Reagent: 2540

Styrene is a well-known commodity chemical and used as a monomer building block with the second most reactions as reactant reported (152930). The number of journal articles (872) and patents (90) in the context of platform chemicals are also comparably high. Its reported production/import volume in the EU is between 1 million and 10 million tonnes per year. The petrochemical route involves the iron (III) catalysed dehydrogenation of ethylbenzene. This method could also be applied to bio-based ethylbenzene monomers obtained from lignin pyrolytic depolymerization [275] or from lignin based pyrolysis oil [276]. As depolymerization of lignin leads to many different phenolic compounds, other routes to produce styrene are also investigated. A biochemical pathway for styrene production could be based on fermentation of glucose to cinnamic acid followed by decarboxylation [277] or metathesis with ethylene [278]. Another alternative route utilizing microbial production is via dehydration of phenyl ethanol produced from glucose [279]. No data on the share of bio-based production of styrene was found. The harmonised classifications of styrene include toxicity to reproductive organs category 2, which makes a future categorization as SOC possible.

Carbon monoxide

Substance Identity

IUPAC-Name: Carbon monoxide
CAS No.: 630-08-0
Mass: 28,01 g mol $^{-1}$
Molecular Formula: CO

Classifications:
Harmonised: Repr. 1A, Press. Gas, Flam. Gas 1, Acute Tox. 3 *, STOT RE 1
Notified: Repr. 1A, Repr. 2, Acute Tox. 2, Acute Tox. 3, Flam. Gas 1, Press. Gas. (Comp.), STOT RE 1

Registration: 1 000 – 10 000 t/a

PACT: DEV 1: Concluded, Nov 2022; DEV 2: Concluded, Nov 2022

Regulatory Obligations (beside REACH/CLP):
Red Flags: Cosmetic Products Regulation
Orange Flags: CMD - Carcinogens and Mutagens Directive, Food Contact Recycled Plastic Materials and Articles Regulation-repealed, Industrial Emissions Directive, Inland Transport of Dangerous Goods Directive, Pesticide Residues Regulation, Plastic Materials and Articles Regulation, Protection of Pregnant and Breastfeeding Workers Directive, Protection of Young People Directive, Recycled Plastic Food Contact Materials

Feedstock: Biomass, CO_2
Production:

Relevance:

Patents: 44

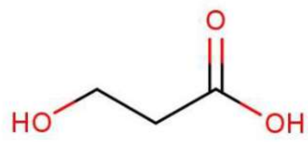
Book/Review: Copper catalysts for CO_2 hydrogenation to CO through reverse water–gas shift reaction for e-fuel production: Fundamentals, recent advances, and prospects, Choi et al., 2024, 10.1016/j.cej.2024.152283 [280]

Sci Finder References: 735
Sci Finder Reactions: Reactant: 143744; Reagent: 13299

Carbon monoxide (CO) has the third highest number of reactions as reactant (143744) reported in SciFinder. The number of search results for journal articles and patents in the context of platform chemicals are 735 and 44. CO is manufactured/imported in volumes of 1 000 to 10 000 tonnes per year in the EU. It is mainly used together with hydrogen gas as so-called synthesis gas or syngas, the production of which can be performed by steam methane reforming. This process can be fuelled by fossil carbon sources such as natural gas as well as by biomass [103]. Alternatively CO can be renewably produced in carbon capture processes via the electro chemical reduction of carbon dioxide [281]. It can be used together with hydrogen gas in syngas for Fischer-Tropsch synthesis, converting it into hydrocarbons, or the well-established production of methanol [262]. No data on the share of bio-based production of carbon monoxide was found. Carbon monoxide could be, based on its current harmonised classifications, a future SVHC.

3-Hydroxypropionic acid

Substance Identity



IUPAC-Name: 3-Hydroxypropionicacid
CAS No.: 503-66-2
Mass: 90.08 g mol $^{-1}$
Molecular Formula: $C_3H_6O_3$

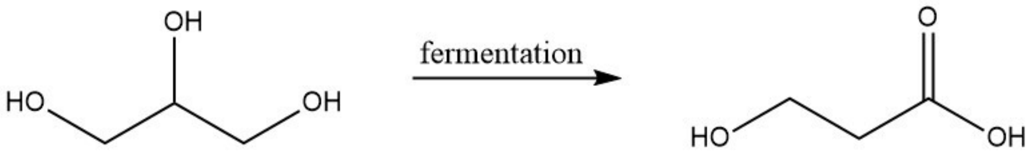
Classifications:
Harmonised: -
Notified: Acute Tox. 4, Skin Irrit.2, Eye Dam. 1, STOT SE3, Not Classified, Eye Irrit. 2

Registration: -

PACT: -

Regulatory Obligations (beside REACH/CLP):
Red Flags: -
Orange Flags: -

Feedstock: Glycerol, Glucose, Xylose
Production:



Relevance:

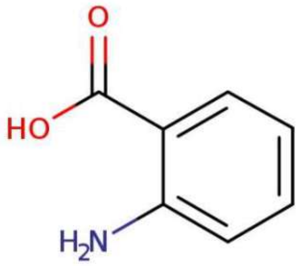
Patents: 290

Book/Review: Biocatalytic gateway to convert glycerol into 3-hydroxypropionic acid in waste-based biorefineries: Fundamentals, limitations, and potential research strategies, Hossain M. Zabed et al. 2023, DOI: 10.1016/j.biotechadv.2022.108075 [282]

Sci Finder References: 3297
Sci Finder Reactions: Reactant: 645; Reagent: 9

3-Hydroxypropionic Acid (3-HPA) is the surveyed platform chemical with the highest number of patents reported. As it was part of the original DOEs report [22] it has received considerable attention, but researchers have investigated biocatalytic production of it since the 1960s. In the EU there are no manufacturing volumes of 3-HPA reported to ECHA, but its estimated market size is around 3.6 million tonnes per year [282]. Its proposed feedstock for microbial synthesis glycerol is cheap and abundantly available thanks to the biodiesel production [33], but alternatively glucose could also be utilized [283]. Another possible feedstock for fermentative production of 3-HPA reported is 1,3-propanediol [284]. Chemical synthesis from the platform chemical levulinic acid has also been proposed [285]. Zabed et al. state in a recent review [282], that there are still some challenges to be dealt with (substrate toxicity, low selectivity,...) and gaps between laboratory and industrial scale experiments. Ultimately though, 3-HPA could be used in the production of many bulk chemicals, such as acrylic acid, acrylamide, acrylonitrile and polymers. According to Grand View Research, the global revenue share of bio-based 3-HPA production was 17.7 % in 2023 [286]. Based on harmonised classifications, there are no reasons for a future categorization of 3-HPA as SVHC, MHC or SOC.

Anthranilic acid



Substance Identity
IUPAC-Name: 2-Aminobenzoic acid
CAS No.: 118-92-3
Mass: 137,14 g mol $^{-1}$
Molecular Formula: $C_7H_7NO_2$

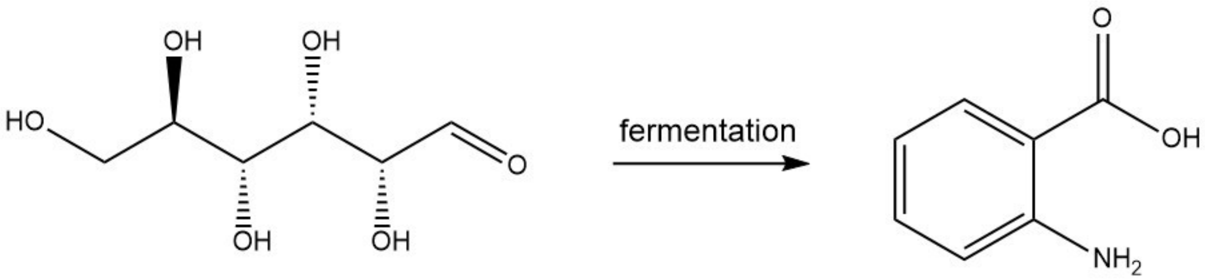
Classifications:
Harmonised: -
Notified: Aquatic Chronic 3, Eye Dam. 1, Eye Irrit. 2, Not Classified, STOT SE 3

Registration: Intermediate only

PACT: -

Regulatory Obligations (beside REACH/CLP):
Red Flags: -
Orange Flags: -

Feedstock: Glucose
Production:



Relevance:

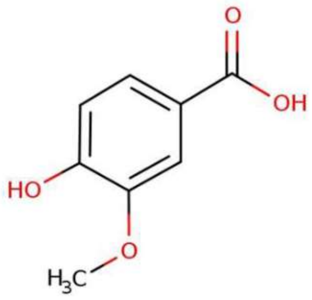
Patents: 249

Book/Review: -

Sci Finder References: 2471
Sci Finder Reactions: Reactant: 14579; Reagent: 94

Anthranilic Acid has been heavily researched as shown by its number of journal articles (2471) and patents (249) found on SciFinder. It is only registered as an intermediate within the EU and has therefore no manufacturing/import volume reported. Anthranilic acid is an aromatic acid containing an amine group and is used in plastic, detergent and pesticides production [287]. Polymers based of anthranilic acid have been reported to be antibacterial and antioxidant making it a potentially interesting material for pharmaceutical applications [288]. It can be produced from fossil based phthalic anhydride via sodium phthalamate followed by oxidative decarboxylation [289]. The proposed bio-based production of it could be achieved biosynthetically using glucose (but also glycerol and lignocellulose are suggested for future research) as a feedstock for different bacterial strains utilizing the shikimate pathway, but as for many aromatic compounds, yields and productivity are far from commercial applications since it is an intermediate not being accumulated within the metabolic pathway [290]. No data on the share of bio-based production of anthranilic acid was found. Based on notified classifications of hazards, the substance could be categorised as a SOC in the future, due to its classification as aquatic chronic 3.

Vanillic acid



Substance Identity
IUPAC-Name: 4-Hydroxy-3-methoxybenzoic acid
CAS No.: 121-34-6
Mass: 168,14 g mol $^{-1}$
Molecular Formula: $C_8H_8O_4$

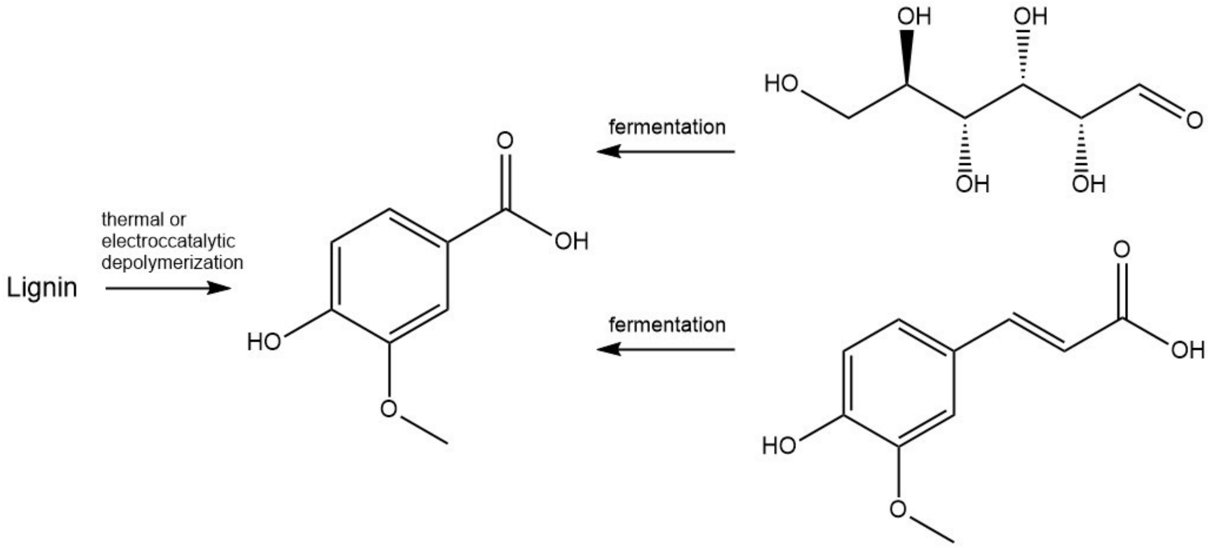
Classifications:
Harmonised: -
Notified: Eye Irrit. 2, Eye Irrit. 2A, Not Classified, Skin Irrit. 2, STOT SE 3, STOT SE 3

Registration: Intermediate only

PACT: -

Regulatory Obligations (beside REACH/CLP):
Red Flags: -
Orange Flags: -

Feedstock: Lignin, Glucose, Ferulic Acid
Production:



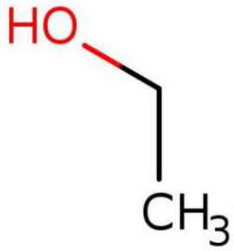
Relevance:

Patents: 248

Book/Review: -

Sci Finder References: 2446
Sci Finder Reactions: Reactant: 1017; Reagent: 4

Vanillic acid is another aromatic acid within the group of platform chemicals with significant interest within academia based on the number of search results for journal articles and patents in SciFinder. It could be utilized as pre-cursor for different aromatic compounds (most famously vanillin) and pharmaceuticals, or as monomer for polyesters [291]. As it has only a registration as intermediate within the EU, there is no manufacturing/import volumes reported. Vanillic acid can be produced petrochemically from eugenol or guaiacol via vanillin or based of lignosulfonates [292]. The proposed sustainable routes are based on either thermal or electrocatalytic lignin degradation [293-295], or microbial conversion of ferulic acid or glucose [296-298], but photocatalytic and other chemical methods to convert ferulic acid have been suggested [299, 300]. Ferulic acid is found in the cell walls of many plants and acts as a crosslink between lignin and hemicellulose; it can be extracted from different agricultural waste streams such as wheat and rice bran [301]. No data on the share of bio-based production of vanillic acid was found. Vanillic acid is registered as intermediate within the EU and has neither harmonised classifications nor any notified classifications which would give ground for a future categorization as SVHC, MHC or SOC.



Ethanol

Substance Identity
IUPAC-Name: Ethanol
CAS No.: 64-17-5
Mass: 46,07 g mol $^{-1}$
Molecular Formula: C_2H_6O

Classifications:
Harmonised: Flam. Liq. 2
Notified: Carc. 1A, Carc. 1B, Muta. 1B, Repr. 1A, Repr. 2, Acute Tox. 3, Acute Tox. 4, Aerosol 1, Aquatic Acute 1, Aquatic Chronic 1, Aquatic Chronic 2, Aquatic Chronic 3, Eye Dam. 1, Eye Irrit. 2, Flam Liq. 2, Flam Liq. 3, Met. Corr. 1, Not Classified, Skin Corr. 1B, Skin Irrit. 2, Skin Sens. 1, STOT RE 1, STOT RE 2, STOT SE 1, STOT SE 2, STOT SE 3

Registration: 10 000 000 – 100 000 000 t/a

PACT: DEV 1: Under Assessment, Apr 2023; DEV 2: Ongoing, Dez 2022; DEV 3: Concluded, Nov 2022; Intention, Jan 2024, Greece

Regulatory Obligations (beside REACH/CLP):
Red Flags: -
Orange Flags: Food Contact Recycled Plastic Materials and Articles Regulation-repealed, Food Contact Regenerated Cellulose Directive, Inland Transport of Dangerous Goods Directive, Plastic Materials and Articles Regulation, Protection of Young People Directive, Recycled Plastic Food Contact Materials

Feedstock: Saccharides
Production:

Relevance:

Patents: 80

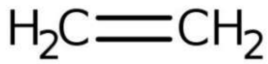
Book/Review: Bioethanol Production, Ayyana et al., 2023, DOI: 10.5772/intechopen.109097 [302]

Sci Finder References: 1767
Sci Finder Reactions: Reactant: 105104; Reagent: 36422

Ethanol is one of the four platform chemicals already produced/imported in the EU in volumes above 10 million tonnes per year. Not only that, but it is already mainly produced by fermentation [241] of renewable feedstocks such as sucrose, starch and cellulose. According to a report by Jaine and Prasad, the share of bio-based production for ethanol was 93 % in 2022 [241]. Alternatively it can be produced by ethylene hydration [303]. The global bio ethanol production is mainly based on Brazilian sugar cane and US American maize, both of which also being important plants for food. As discussed in earlier chapters, alternative feedstocks such as lignocellulosic and algae biomass should be preferably used and are extensively researched, but the challenges of high energy pretreatment methods and high enzyme cost still exist [45, 83, 110, 252, 302, 304-306]. Biological pretreatment methods offer mild conditions but suffer from long pretreatment time and low efficiency [304]. Hoang et al. suggested in a recent review [307] the use of municipal solid waste (MSW) for bioethanol production (as one way to utilize MSW), but also mention the high-cost and high energy demand. Ethanol can act as a platform for the production of many different chemicals including ethylene (and other olefins), acetic acid, aromatics, acetaldehyde and others [308]. It should be of no surprise that 105104 reactions are reported on SciFinders search engine using ethanol as reactant. Based on current harmonised classifications, there are no reasons for a future categorization of ethanol as SVHC, MHC or SOC.

Ethylene

Substance Identity
IUPAC-Name: Ethylene
CAS No.: 74-85-1
Mass: 28,05 g mol $^{-1}$
Molecular Formula: C_2H_4



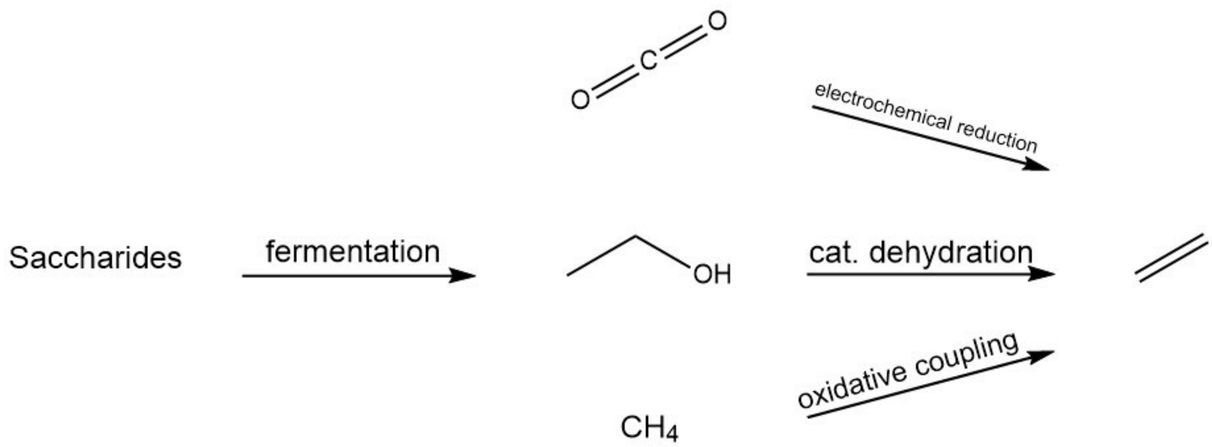
Classifications:
Harmonised: Press. Gas, Flam. Gas 1, STOT SE 3
Notified: Flam. Gas 1, Not Classified, Press. Gas (Comp.), Press. Gas (Liq.), Press. Gas (Ref. Liq.), STOT SE 2, STOT SE 3

Registration: 10 000 000 – 100 000 000 t/a

PACT: DEV 1: Under Assessment, Jun 2022; DEV 2: -, Aug 2021; DEV 3: Concluded, Nov 2022; DEV 4: Concluded, Nov 2022

Regulatory Obligations (beside REACH/CLP):
Red Flags: -
Orange Flags: Food Contact Recycled Plastic Materials and Articles Regulation-repealed, Inland Transport of Dangerous Goods Directive, Pesticide Residues Regulation, Plastic Materials and Articles Regulation, PPPR - Plant Protection Products Regulation, Protection of Young People Directive, Recycled Plastic Food Contact Materials

Feedstock: Saccharides
Production:



Relevance:

Patents: 64

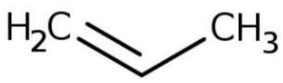
Book/Review: Critical review: ‘Green’ ethylene production through emerging technologies, with a focus on plasma catalysis, Lamichhane et al., 2024, DOI: 10.1016/j.rser.2023.114044 [309]

Sci Finder References: 803
Sci Finder Reactions: Reactant: 63285; Reagent: 2135

Ethylene is one of the most important commodity chemicals in petroleum based chemical industry and manufactured/imported in volumes of over 10 million tonnes per year in the EU. The global bio-based share of production was estimated to be 0.03% by the JRC [24]. Steam cracking of natural gas is the main production method of ethylene, which besides being based on fossil resources produces significant amounts of CO_2 [310]. The three considered feedstocks for bio-based ethylene are methane from biogas plants, ethanol from fermentation of saccharides and captured CO_2. Teixeira Penteado et al. investigated the economic potential of ethylene based on oxidative coupling of methane (OCM) and based on their estimations concluded the process to be a bridging technology enabling to use renewable feedstocks for traditional chemistry as we develop new bio-based chemicals [311]. The dehydration of ethanol to yield ethylene is a well-established reaction but necessitates the ethanol to have a certain level of purity, which is not always achieved in bioethanol production. Nevertheless, dehydration of ethanol from starch and sugar as well as lignocellulosic biomass could be a feasible alternative to fossil ethylene [312]. Furthermore several companies have already commercial processes set up and running based on ethanol dehydration [313]. The electrochemical reduction of CO_2 to ethylene is also a promising technology, but by-product formation and high energy consumption in separation and purification processes are challenges to be overcome [314]. Bio-based ethylene could lead to a number of other bio-based platform molecules, including propylene, butenes and BTX aromatics, acting as important drop-in chemicals within the petroleum based chemical industry [258]. Based on harmonised classifications and notified classifications, there are no reasons for a future categorization as SVHC, MHC or SOC.

Propylene

Substance Identity
IUPAC-Name: Propylene
CAS No.: 115-07-1
Mass: 42,08 g mol $^{-1}$
Molecular Formula: C_3H_6



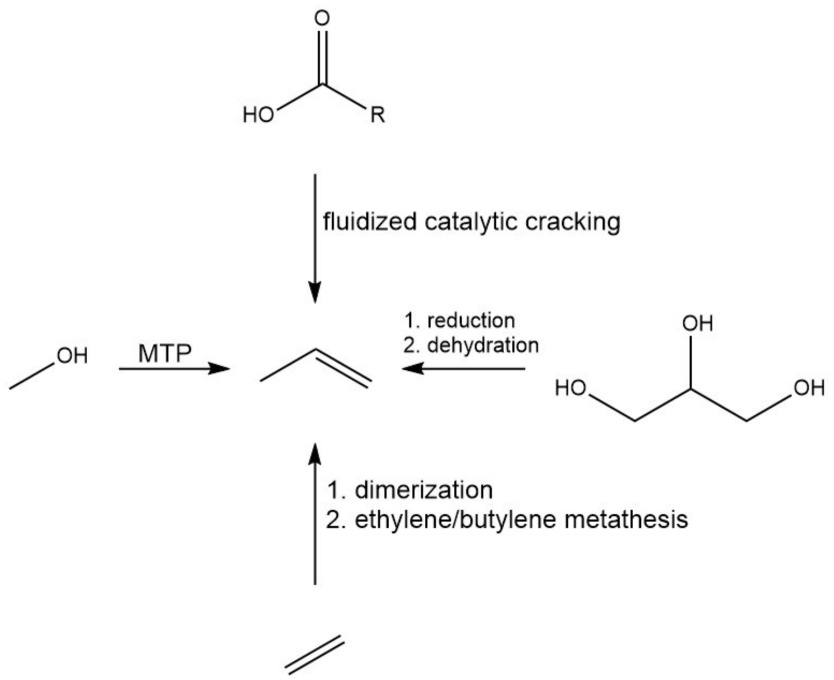
Classifications:
Harmonised: Press. Gas, Flam. Gas 1
Notified: Flam. Gas 1, Not Classified, Press. Gas (Comp.), Press. Gas (Liq.), STOT SE 3

Registration: 10 000 000 – 100 000 000 t/a

PACT: DEV 1: Concluded Dez 2023; DEV 2: Under Assessment, Apr 2022; DEV 3: Concluded, Nov 2022; DEV 4: Concluded Nov 2022; DEV 5: Concluded Nov 2022

Regulatory Obligations (beside REACH/CLP):
Red Flags: -
Orange Flags: Food Contact Recycled Plastic Materials and Articles Regulation-repealed, Inland Transport of Dangerous Goods Directive, Plastic Materials and Articles Regulation, Protection of Young People Directive, Recycled Plastic Food Contact Materials

Feedstock: Glycerol (via Propanol), Syngas (via Methanol), Fatty Acids/Esters, Ethanol (via Ethylene/Butylene Metathesis)
Production:



Relevance:

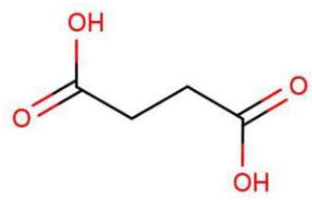
Patents: 20

Book/Review: Strategies to control reversible and irreversible deactivation of ZSM-5 zeolite during the conversion of methanol to propylene (MTP): A review, Zabihpour et al., 2023, DOI: 10.1016/j.ces.2023.118639 [315]

Sci Finder References: 273
Sci Finder Reactions: Reactant: 22587; Reagent: 359

Propylene is another proposed green platform chemical with a production/import volume of over 10 million tonnes per year in the EU. Similarly to ethylene, it is one of the most important building blocks in petrochemical processes and was mainly produced from steam cracking of natural gas and fluid-catalytic cracking process. The amount produced by propane dehydrogenation, methanol-to-propene (MTP) and methanol-to-olefine (MTO) displayed a significant increase in the last decade due to low-cost feedstock [316]. Proposed manufacturing methods for propylene based of renewable feedstocks are via butylene/ethylene metathesis, MTP, catalytic cracking of vegetable oils or conversion of glycerol [262]. There has been significant attention on hydrodeoxygenation of glycerol over the last years utilizing molybdenum-based catalysts on laboratory scale [317]. Metathesis of butene with ethylene to form propylene is based on the dehydration of ethanol, followed by dimerization to butene. Phung et al. discuss the process and utilized zeolite catalysts in a recent review [318] in detail and conclude the technology to be important in the near future of biorefining. Catalytic cracking of used cooking oil is a process already implemented by Neste Oyj in Finland, utilizing a waste stream [319]. The methanol-to-olefins process is already well established [316] and utilizes either H-ZSM-5 and SAPO-34 catalysts [270, 320]. Propylene could be further refined to yield different commodity chemicals (propylene oxide, acrylonitrile, cumene, isopropanol), but its main application is polypropylene production. No data on the share of bio-based production of propylene was found. Based on harmonised classifications and notified classifications, there are currently no reasons for a future categorization as SVHC, MHC or SOC.

Succinic acid



Substance Identity
IUPAC-Name: Butanedioic acid
CAS No.: 110-15-6
Mass: 118.09 g mol $^{-1}$
Molecular Formula: $C_4H_6O_4$

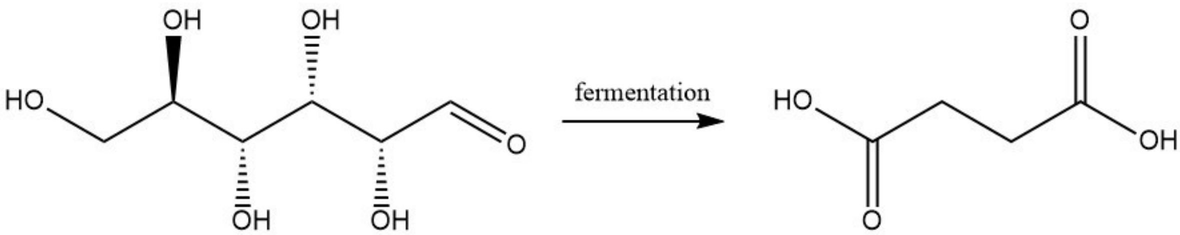
Classifications:
Harmonised: -
Notified: Carc. 1B, Muta. 1B, Repr. 2, Acute Tox. 3, Aquatic Chronic 3, Asp. Tox. 1, Eye Dam. 1, Eye Irrit. 2, Eye Irrit. 2A, Not classified, Skin Corr. 1C, Skin Irrit. 2, STOT SE 3

Registration: 10 000 - 100 000 t/a

PACT: -

Regulatory Obligations (beside REACH/CLP):
Red Flags: -
Orange Flags: Food Contact Recycled Plastic Materials and Articles Regulation-repealed, Plastic Materials and Articles Regulation, Recycled Plastic Food Contact Materials

Feedstock: Glucose
Production:



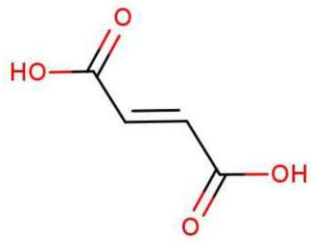
Relevance:

Patents: 26

Book/Review: Production of succinic acid by metabolically engineered microorganisms, Jung Ho Ahn et al., 2016, DOI: 10.1016/j.copbio.2016.02.034 [321]

Sci Finder References: 307
Sci Finder Reactions: Reactant: 9692; Reagent: 504

Mentioned in the original report by the DOE in 2004 [22], succinic acid is already manufactured/imported in volumes of 10 000 to 100 000 tonnes per year within the EU. Not only is it produced in high volumes, but within the EU the share of succinic acid manufactured based of renewable resources was estimated by the JRC to be 100% [24]. Before the bio-based production methods were feasible, succinic acid was produced by catalytic hydrogenation of maleic anhydride, followed the hydration of succinic anhydride [322]. The maleic anhydride is produced by oxidation of n-butane or benzene [323]. The industrial bio-based production can use glucose (some with CO_2 as co-substrate) as carbon source for metabolically engineered microorganisms, but glycerol and xylose could also be utilized [324-326]. However, separation of succinic acid from the fermentation broth is a complex and challenging task that influences its production cost heavily [327-329]. In a recent review Kumar et al. [330] summarise and discuss traditional methods, and suggest a multistep membrane-based process as a greener approach of separation and purification. An important potential bio-based chemical derived from succinic acid is 1,4-butanediol, which can be further used to produce γ-butyrolactone, THF, 2-pyrrolidone and N-methyl-2-pyrrolidone. Direct routes to the latter are also investigated as well as many possible applications in bio-based polymers [322, 331, 332]. There are no harmonised classifications found within ECHA's public database as well as no entries within PACT. The notified classifications include some as CMR, which could lead to a future categorization as SVHC (as well as MHC and SOC) if those are to be harmonised. Succinic acid is a versatile molecule, its production could be based of different renewable resources including waste streams and mild reaction conditions, making it a potentially "green" platform chemical for the future.



Fumaric acid

Substance Identity
IUPAC-Name: (2E)-butenedioic acid
CAS No.: 110-17-8
Mass: 116.07 g mol $^{-1}$
Molecular Formula: $C_4H_4O_4$

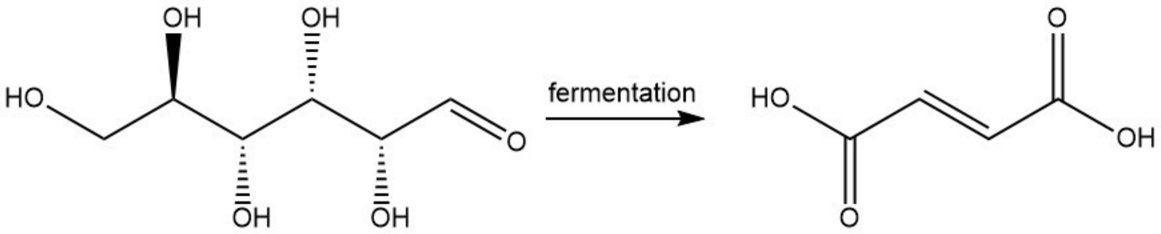
Classifications:
Harmonised: Eye Irrit. 2
Notified: Acute Tox. 4, Eye Irrit. 2, Eye Irrit. 2A, Not classified, Skin Irrit. 2, STOT SE 3

Registration: 10 000 - 100 000 t/a

PACT: DEV 1: Conclude, Nov 2022, DEV 2: Conclude, Nov 2022, DEV 3: Conclude, Nov 2022

Regulatory Obligations (beside REACH/CLP):
Red Flags: -
Orange Flags: Food Contact Recycled Plastic Materials and Articles Regulation-repealed, Plastic Materials and Articles Regulation, Recycled Plastic Food Contact Materials

Feedstock: Glucose
Production:



Relevance:

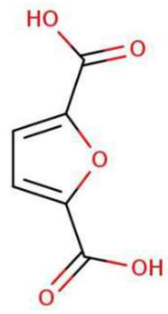
Patents: 21

Book/Review: Fumaric acid production: a biorefinery perspective, Victor Martin-Dominguez et al., 2018, DOI: 10.3390/fermentation4020033 [333]

Sci Finder References: 149
Sci Finder Reactions: Reactant: 14012; Reagent: 749

Fumaric acid is another diacid mentioned in the DOEs report [22]. It is manufactured/imported in the EU in volumes of 10 000 to 100 000 tonnes per year. The most common production methods are thermal or catalytic isomerization of fossil based maleic acid, but also to some extent by fermentation of monosaccharides [323]. For the bio-based production of fumaric acid, mainly fungal species are proposed, which are already used in other fermentation processes, but alternative microorganisms are also being explored. Examined carbon sources include glucose, xylose and glycerol [334]. Downstream processing is, as for most platform chemicals produced by fermentation, still considered an obstacle to be overcome for economically feasible bio-based production [335]. Fumaric acid is often used in polyesters, but also its direct applications in food industry and the utilization of its esters in pharmaceutical industry are of importance [333]. No data on the share of bio-based production of fumaric acid was found. The harmonised classifications reported and found in ECHA's public database are no basis for a future categorization as SVHC, MHC or SOC.

2,5-Furandicarboxylic acid



Substance Identity
IUPAC-Name: 2,5-Furandicarboxylicacid
CAS No.: 3238-40-2
Mass: 156.09 g mol $^{-1}$
Molecular Formula: $C_6H_4O_5$

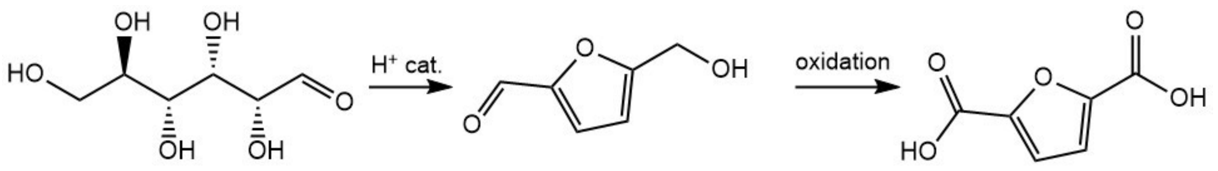
Classifications
Harmonised:
Notified: Eye Irrit. 2, Eye Irrit. 2A, Skin Irrit. 2, STOT SE 3

Registration: 10 - 100 t/a

PACT: Dev 1: Information requested, Mär 2024; Dev 2: Concluded, Nov 2022; Dev 3: Concluded, Nov 2022; ARN: ECHA, CCH, GMT 326

Regulatory Obligations:
Red Flags: -
Orange Flags: Food Contact Recycled Plastic Materials and Articles Regulation-repealed, Plastic Materials and Articles Regulation, Recycled Plastic Food Contact Materials

Feedstock: Glucose
Production:



Relevance:

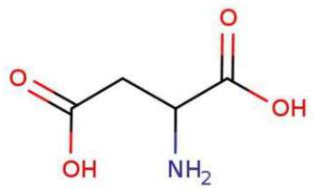
Patents: 7

Book/Review: Recent Advances in the Catalytic Synthesis of 2,5-Furandicarboxylic Acid and Its Derivatives, Zehui Zhang et al., 2015, DOI: 10.1021/acscatal.5b01491 [336]

Sci Finder References: 162
Sci Finder Reactions: Reactant: 2288; Reagent: 1

2,5-Furandicarboxylic acid is a biomass derived chemical mentioned in the DOEs report [22] with a manufacturing/import volume of 10 to 100 tonnes per year in the EU. It is produced as a substitute for terephthalic acid in polyethylene terephthalate (PET) leading to polyethylene furan-2,5-dicarboxylate (PEF) by oxidation of hydroxymethylfurfural based of fructose. Alternative routes are also available, using the different feedstocks such as glucose, xylose or cellulose, or using different intermediates such as 5-methoxymethylfurfural, furfural or 2-furanoic acid. Industrial production is mainly based on heterogeneous catalytic oxidation of HMF [337]. Whole-cell and enzymatic processes are usually preferred because of the milder reaction conditions and non-toxic by-products and intermediates, but they still suffer from lower yields and more complex downstream processing. Due to the two different oxidation steps (alcohol and aldehyde), cascading oxidations using multiple enzymes are necessary [338]. Whole-cell catalysis would offer one step reactions from HMF to FDCA, but they were not researched as thoroughly. Electrochemical and photocatalytic methods are both promising greener methods compared to the currently used ones but are still only examined at laboratory scale [339]. 2,5-FDCAs main envisioned use is as a monomer directly substituting terephthalic acid, leading to PEF as prospective substitute to PET also displaying favourable polymer properties, but it could also be used in the production of many other chemicals due to its diacid functionality and cyclic structure [337]. No data on the share of bio-based production of 2,5-FDCA was found. The only production pathways found in literature were based on biomass. Based on harmonised classifications and notified classifications found in ECHA's public database, there are no reasons for a future categorization as SVHC, MHC or SOC.

Aspartic acid



Substance Identity
IUPAC-Name: 2-Aminobutanedionic acid
CAS No.: 56-84-8
Mass: 133.1 g mol $^{-1}$
Molecular Formula: $C_4H_7NO_4$

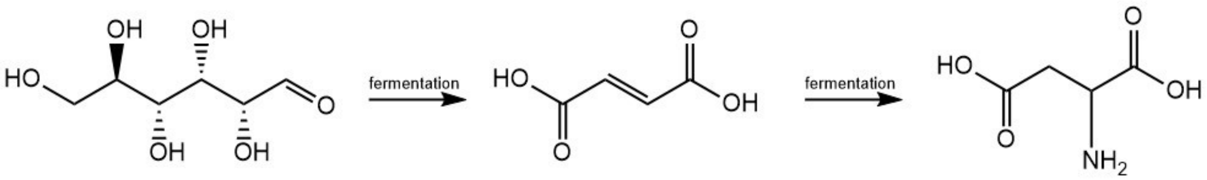
Classifications
Harmonised:
Notified: Eye Irrit. 2, Not classified, Skin Irrit. 2

Registration: 1 000 – 10 000 t/a

PACT: ARN ECHA, No action, GMT 421

Regulatory Obligations (beside REACH/CLP):
Red Flags: -
Orange Flags: -

Feedstock: Glucose, Protein hydrolysate
Production:



Relevance:

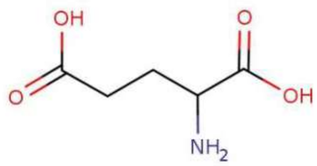
Patents: 17

Book/Review: Recent advances in the metabolic engineering and physiological opportunities for microbial synthesis of L-aspartic acid family amino acids: A review, Yusheng Wang et al., 2023, DOI: 10.1016/j.ijbiomac.2023.126916 [340]

Sci Finder References: 346
Sci Finder Reactions: Reactant: 3425; Reagent: 103

Aspartic acid is an amino acid mentioned as platform chemical in the DOEs report [22], which is manufactured/imported in the EU in volumes of 1 000 to 10 000 tonnes per year. Industrially, aspartic acid is produced from fumaric acid (which can be derived from biomass) and ammonia utilizing aspartase containing cells [341]. Guang-Hui et al. developed a one-pot method using cascading photo-, electro- and biocatalysis for synthesis of different C4 chemicals starting from furfural which achieved a 97% yield of aspartic acid on laboratory scale [342]. Direct fermentation utilizing cheaper feedstocks such as glucose are rarely researched, and the yields are low compared to the methods above due to it being an important intermediate of many metabolic pathways [343]. Aspartic acid is an important building block for the production of pharmaceuticals and chemicals, but also in food industry for the production of aspartame [343]. In all aforementioned production methods ammonia is used as a nitrogen source, which is mostly based of the fossil based Haber-Bosch process to date, but could be produced via biomass gasification [344]. No data on the share of bio-based production of aspartic acid was found. Based on harmonised classifications and notified classifications found in ECHA's public database, there are no indications for a future categorization as SVHC, MHC or SOC.

Glutamic acid



Substance Identity
IUPAC-Name: 2-Aminopentanedionic acid
CAS No.: 56-86-0
Mass: 147.13 g mol $^{-1}$
Molecular Formula: $C_5H_9NO_4$

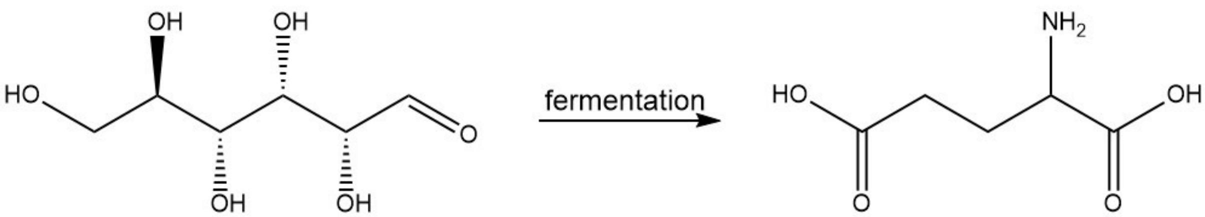
Classifications
Harmonised:
Notified: Acute Tox. 4, Eye Irrit. 2, Eye Irrit. 2A, Not classified, Skin Irrit. 2, STOT SE 3

Registration: 100 – 1000 t/a

PACT: ARN ECHA, No action, GMT 421

Regulatory Obligations (beside REACH/CLP):
Red Flags: -
Orange Flags: -

Feedstock: Glucose, Protein hydrolysate
Production:



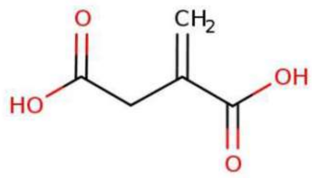
Relevance:

Patents: 13

Book/Review: Production and purification of glutamic acid: A critical review towards process intensification, Ramesh Kumar et al., 2014, DOI: 10.1016/j.cep.2014.04.012 [345]

Sci Finder References: 386
Sci Finder Reactions: Reactant: 416; Reagent: 8

Glutamic acid is a non-essential amino acid mentioned as platform chemical in the DOEs report [22] and manufactured/imported in volumes of 100 to 1 000 tonnes per year in the EU. On large scale, glutamic acid is produced by fermentation of sugars. The main bacterial strains used are *Brevibacterium flavum*, *Corynebacterium glutamicum* and *Corynebacterium sclerophylla*. The production process including downstream processing has been well established, different feedstocks though are still being explored to further decrease costs [346]. The use of protein rich biomass (including waste streams) to extract and hydrolyse proteins for glutamic acid production and utilization has been discussed by Lammens et al. [53] in 2012 and again in more detail and all N-containing compounds in 2021 by Bayah et al. [347]. Glutamic acid could be used for the production of nitrogen containing bulk chemicals such as N-methylpyrrolidone [53], which is especially interesting since the Haber-Bosch process is based on fossil resources and has a high energy demand. No data on the share of bio-based production of glutamic acid was found. The only production pathways found in the literature were based on biomass. Based on harmonised classifications and notified classifications found in ECHA's public database, there are no indications for a future categorization as SVHC, MHC or SOC.



Itaconic acid

Substance Identity
IUPAC-Name: Methylidenebutanedioic acid
CAS No.: 97-65-4
Mass: 130.1 g mol^{-1}
Molecular Formula: $C_5H_6O_4$

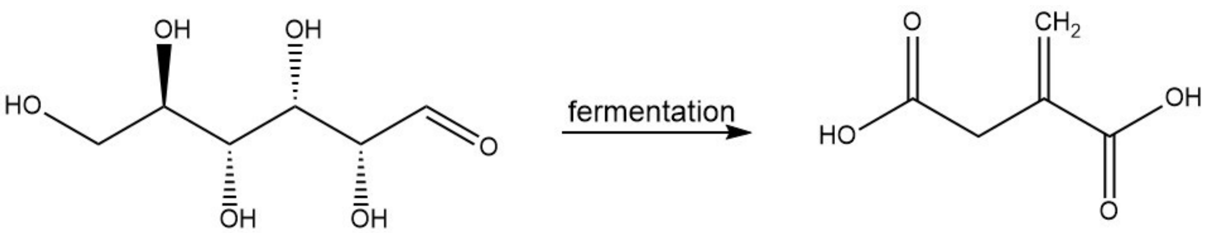
Classifications
Harmonised:
Notified: Acute Tox. 2, Aquatic Acute 1, Aquatic Chronic 1, Eye Dam. 1, Eye Irrit. 2, Not Classified, Skin Irrit. 2, STOT SE 3

Registration: 10 000 – 100 000 t/a

PACT: DEV 1: Concluded, Nov 2022; DEV 2: Concluded, Nov 2022

Regulatory Obligations (beside REACH/CLP):
Red Flags: -
Orange Flags: Food Contact Recycled Plastic Materials and Articles Regulation-repealed, Plastic Materials and Articles Regulation, Recycled Plastic Food Contact Materials

Feedstock: Glucose
Production:



Relevance:

Patents: 12

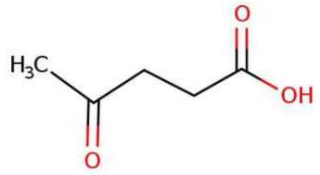
Book/Review: Itaconic acid - a versatile building block for renewable polyesters with enhanced functionality, Tobias Robert et al., 2016, DOI: 10.1039/c6gc00605a [348]

Sci Finder References: 130
Sci Finder Reactions: Reactant: 7707; Reagent: 58

Itaconic acid is an unsaturated diacid mentioned as platform chemical in the DOEs report [22] and manufactured in a volume of 10 000 to 100 000 tonnes per year in the EU. It is produced on industrial scale by fermentation of glucose by *Aspergillus terreus*. Different fungal species have been investigated for the process, but none of them had high enough yields. Other substrates than glucose have been investigated to evade the conflicting use for food production, namely carbohydrate rich waste streams and lignocellulosic residues [349]. Another reason for the exploration of cheaper feedstocks is the decrease of production costs, but the achieved itaconic acid yields are low compared to pure sugar solutions [350]. The main challenges for the use of waste streams are the variable composition of substrates, crude substrate delivering lower yields and harmful substances for the use of microorganisms in the feedstock [349]. Chemical production routes based on citric acid have too low yields and the feedstock is considerably more expensive than for fermentative methods, making it not feasible for large scale production [349]. The main application of itaconic is in polyester production, but also other uses as monomers for hydrogels in medical applications have been envisioned [351]. A potential use as reactant in synthesis for chemicals could be in synthesis of N-alkyl/arylcarboxypyrrolidones or 2-methylsuccinic acid [352]. No data on the share of bio-based production of itaconic acid was found. The only production pathways found in the literature were based on biomass. Based on harmonised classifications and notified classifications found in ECHA's public database, there are currently no reasons for a future categorization as SVHC, MHC or SOC. A future categorization as SOC could be possible based on the notified classification as aquatic chronic 1.

Levulinic acid

Substance Identity
IUPAC-Name: 4-Oxopentanoic acid
CAS No.: 123-76-2
Mass: 116.12 g mol $^{-1}$
Molecular Formula: $C_5H_8O_3$



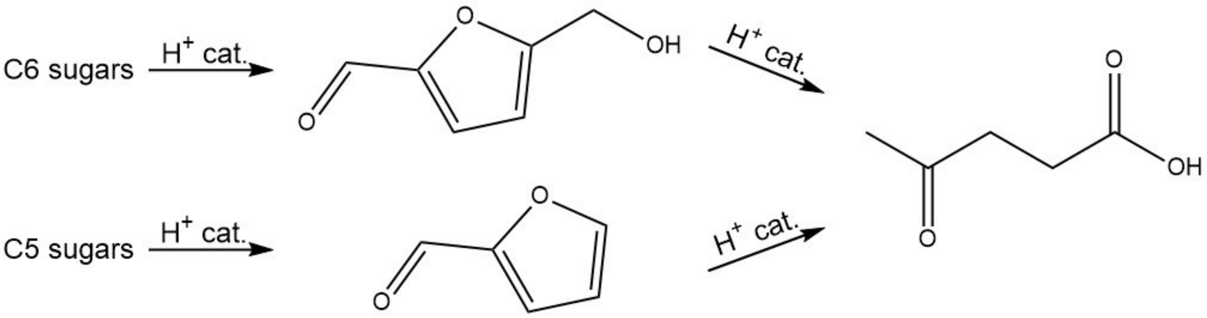
Classifications:
Harmonised: -
Notified: Acute Tox. 4, Eye Dam. 1, Eye Irrit. 2, Eye irrit. 2A, Met. Corr. 1, Skin Corr. 1B, Skin Corr. 1C, Skin Irrit. 2, Skin Sens. 1, STOT SE 3

Registration: 100 - 1 000 t/a

PACT: DEV 1: Concluded, Nov 2022; DEV 2: Concluded, Mär 2023

Regulatory Obligations (beside REACH/CLP):
Red Flags: -
Orange Flags: Food Contact Recycled Plastic Materials and Articles Regulation-repealed, Plastic Materials and Articles Regulation, Recycled Plastic Food Contact Materials

Feedstock: Sugars (C5/C6)
Production:



Relevance:

Patents: 22

Book/Review: Levulinic Acid – A sustainable platform chemical for value added products, Claudio J.A. Mota, DOI: 10.1002/9781119814719 [353]

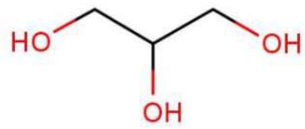
Sci Finder References: 449
Sci Finder Reactions: Reactant: 9692; Reagent: 504

Levulinic is a ketoacid mentioned as platform chemical in the DOEs report [22] and manufactured/imported in a volume of 100 to 1 000 tonnes per year in the EU. The interest in levulinic acid as a versatile platform chemical has led to the writing of a book by Mota et al. extensively discussing its production, utilization and challenges involved in all steps [353]. It is produced industrially from carbohydrate rich biomass. Polysaccharides are hydrolysed to obtain glucose which is further isomerized to fructose. Heating leads to dehydration to form 5-hydroxymethylfurfural which is decarboxylated to form levulinic acid and formic acid. The separation of levulinic acid from the reaction mixture is performed by distillation, which is simple, but energy intensive. Therefore alternatives to purify the product are researched [354].

Another alternative for easier separation is the use of alcohols as hydrolysing agents leading to levulinate esters with a lower boiling point making distillation less energy intensive [244]. Pentoses can also be used to produce levulinic acid. They are dehydrated to furfural, reduced to furfuryl alcohol and then oxidized to yield the final product [244]. A biotechnological route is fermenting glucose to pyruvic acid, followed by an aldol condensation with acetaldehyde and multiple steps to obtain levulinic acid have been envisioned, but not applied in production. Another chemical route not applied anymore utilizes maleic acid as feedstock [353]. Levulinic acid can be applied in many fields including the production of chemicals like 1,4-pentanediol, angelica lactone, levulinate esters, N-alkyl and N-aryl-2-methylpyrolidones to name a few mentioned in the literature [244, 353]. No data on the share of bio-based production of levulinic acid was found. The only production pathways found in the literature were based on biomass. Based on harmonised classifications found in ECHA's public database, there are currently no reasons for a future categorization as SVHC, MHC or SOC. A future categorization as SOC could be possible based on the notified classification as substance causing skin sensitisation 1.

Glycerol

Substance Identity
IUPAC-Name: 1,2,3-Propanetriol
CAS No.: 56-81-5
Mass: 92.09 g mol $^{-1}$
Molecular Formula: $C_3H_8O_3$



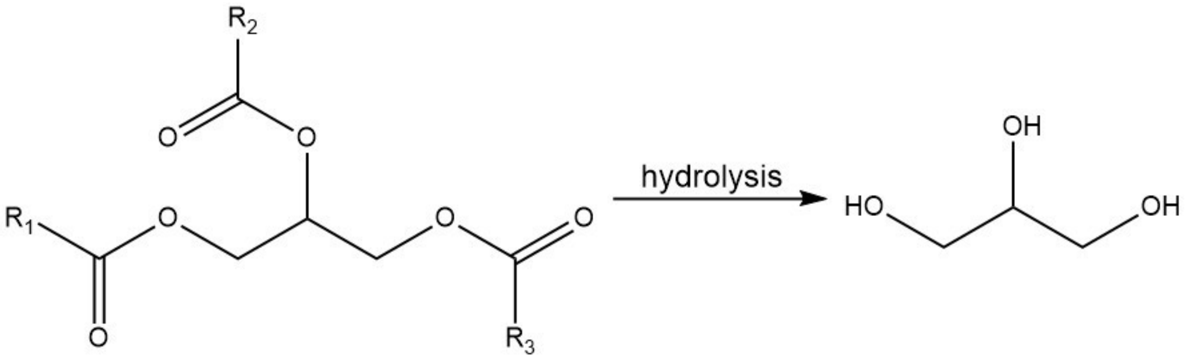
Classifications:
Harmonised: -
Notified: Acute Tox. 2, Acute Tox. 4, Eye Dam. 1, Eye Irrit. 2, Eye Irrit. 2A, Not Classified, Skin Corr. 1, Skin Irrit. 2, STOT RE 1, STOT RE 2, STOT SE 3

Registration: 1 000 - 10 000 t/a

PACT: DEV concluded Nov 2022

Regulatory Obligations (beside REACH/CLP):
Red Flags: -
Orange Flags: Food Contact Recycled Plastic Materials and Articles Regulation-repealed, Food Contact Regenerated Cellulose Directive, Plastic Materials and Articles Regulation, Recycled Plastic Food Contact Materials

Feedstock: Triacylgylcerides
Production:



Relevance:

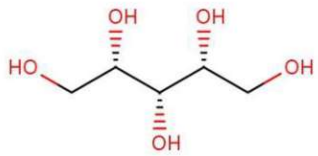
Patents: 48

Book/Review: An Overview of Recent Research in the Conversion of Glycerol into Biofuels, Fuel Additives and other Bio-Based Chemicals, Usman Idis Nda-Umar et al., 2019 DOI: 10.3390/catal9010015 [355]

Sci Finder References: 557
Sci Finder Reactions: Reactant: 20835; Reagent: 3371

Glycerol is a platform chemical mentioned in the DOEs report [22] with a reported manufacture/import volume of 1 000 to 10 000 tonnes per year in the EU. It is a side product in the catalytic transesterifications of fats and oils with methanol in the biodiesel production, but also in the manufacturing of soaps. In some cases, the use of ethanol instead of ethanol is also reported. The increased production of biodiesel also leads to an increase in glycerol supply, making it a cheap platform chemical. Crude glycerol, as it is obtained in biodiesel production, needs to be further purified as it contains alcohol (usually methanol), soap, moisture and other impurities [356]. The full purification process basically precipitates salts, fats and fatty acids, and removes alcohol to further concentrate the glycerol by evaporation [357]. Methods for the final purification are vacuum distillation, ion exchange, membrane separation, adsorption with activated carbon, electrodialysis, coagulation or a combination of them depending on the required purity [358]. As the purification is one of the biggest challenges of glycerol utilization, many researchers explore options to use the crude product for the production of ethanol, citric acid, erythritol, hydrogen and 1,3-propanediol [359-366]. For glycerol with higher purity, chemical synthesis based of propene can be used [367]. High purity glycerol has many possible applications and possibilities to be transformed into higher value-added chemicals such as 1,3-propanediol, glycerol carbonate and acrolein via biotechnological and chemical methods [355, 368]. No data on the share of bio-based production of glycerol was found. Based on harmonised classifications found in ECHA's public database, there are no reasons for a future categorization as SVHC, MHC or SOC. The notified classifications could give reason to classify glycerol as SOC and MHC in the future.

Xylitol



Substance Identity
IUPAC-Name: Xylitol
CAS No.: 87-99-0
Mass: 152.15 g mol $^{-1}$
Molecular Formula: $C_5H_{12}O_5$

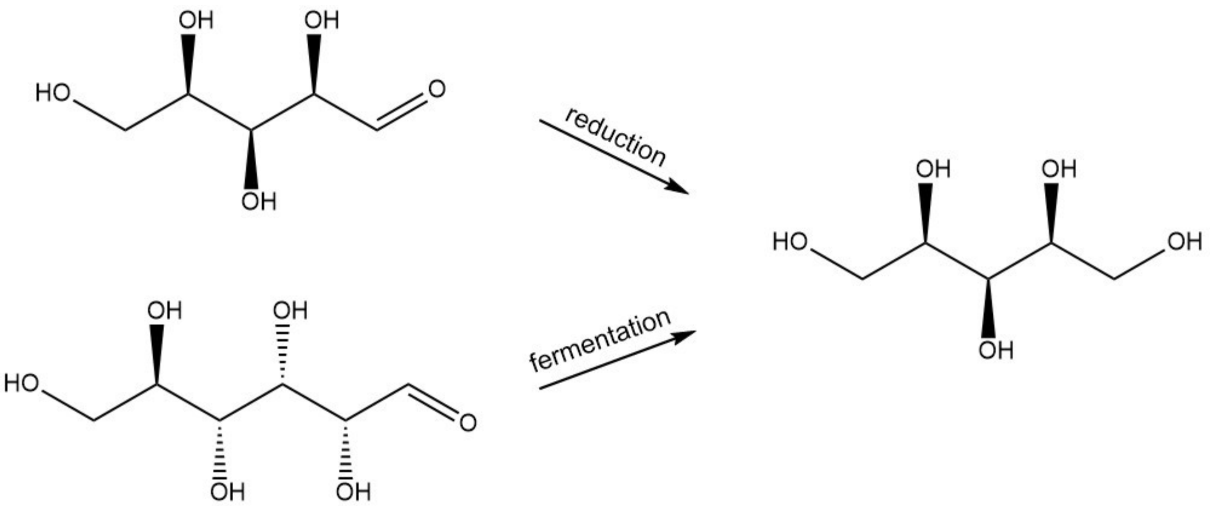
Classifications:
Harmonised: -
Notified: Not classified

Registration: 1 000 - 10 000 t/a

PACT: -

Regulatory Obligations (beside REACH/CLP):
Red Flags: -
Orange Flags: -

Feedstock: Xylose, Glucose
Production:



Relevance:

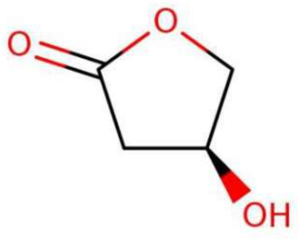
Patents: 3

Book/Review: Xylitol: A review on the progress and challenges of its production by chemical route, Yaimé Delgado Arcaño et al., 2020, 10.1016/j.cattod.2018.07.060 [369]

Sci Finder References: 44
Sci Finder Reactions: Reactant: 782; Reagent: 25

Xylitol is a polyol proposed as platform chemical in the DOEs report [22] with a reported manufacture/import volume of 1 000 to 10 000 tonnes per year in the EU. It is produced on large scale by catalytic hydrogenation of D-xylose using Raney nickel catalysts and harsh conditions [370], but also biotechnological methods can be applied for the same feedstock [371]. The purity of the feedstock is a challenge as it is the case for many bio-based chemicals. The separation of hemicellulose from the lignocellulosic biomass is simple, but hemicellulose hydrolysates contain many different compounds inhibiting microbial growth [372]. To deal with these substances, some researchers suggest to detoxify the hydrolysates by treatment with various adsorbents [373] or changing hydrolysis parameters [374]. Another approach examined by researchers is the one step conversion of glucose to xylitol, but the yields of these methods are significantly lower [375, 376]. Proposed applications for xylitol include (but are not limited to) production of surfactants [377], polymers for tissue engineering [378] and the production of bulk chemicals such as ethylene glycol and 1,2-propanediol [379]. It is already applied directly as low calorie sweetener and in the pharmaceutical industry [380]. No data on the share of bio-based production of xylitol was found. The only production pathways found in the literature were based on biomass. Based on harmonised classifications and notified classifications found in ECHA's public database, there are currently no reasons for a future categorization as SVHC, MHC or SOC.

(S)-3-Hydroxybutyrolactone



Substance Identity
IUPAC-Name: (4S)-4-hydroxyoxolan-2-one
CAS No.: 7331-52-4
Mass: 102.09 g mol $^{-1}$
Molecular Formula: $C_4H_6O_3$

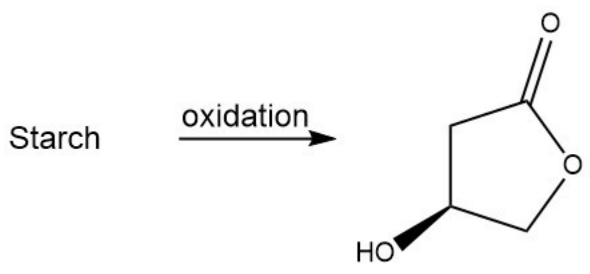
Classifications:
Harmonised: Skin Sens. 1
Notified: Skin Sens. 1

Registration: Confidential

PACT: -

Regulatory Obligations (beside REACH/CLP):
Red Flags: -
Orange Flags: Protection of Young People Directive

Feedstock: Starch
Production:



Relevance:

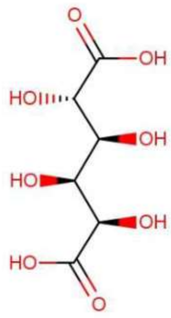
Patents: 2

Book/Review: -

Sci Finder References: 16
Sci Finder Reactions: Reactant: 158; Reagent: 0

(S)-3-Hydroxybutyrolactone (3HγBL) is a platform chemical mentioned in the DOEs report [22] with a confidential manufacturing/importing volume in the EU. 3HγBL can be produced by different methods from fossil feedstocks. Lipase catalysed asymmetric dechlorination, hydrolysis and lactonization of racemic 4-chloro-3-hydroxybutyrate can achieve high enantiomeric excess (ee%), so can heterogeneous catalytic hydrogenation of L-malic acid (which could also be sourced from renewable chemicals) [381], but they suffer from expensive raw materials and complicated purification processes [382]. Both challenges can be addressed by biosynthetic methods using simple saccharides as feedstock, which is why researchers focus on these approaches utilizing recombinant *Escherichia coli* with glucose as carbon source [383, 384]. Another approach is the fermentation of xylose to 3,4-hydroxybutyric acid which is then further lactonized to 3HγBL, however there is still room for yield improvement but optically pure product (ee% > 99.0%) could be obtained [382, 385, 386]. The applications of 3HγBL are as chiral building block for the production of many different pharma- and nutraceuticals [381]. No data on the share of bio-based production of 3HγBL was found. Based on harmonised classifications and notified classifications found in ECHA's public database, 3HγBL could be categorised as SOC in the future due to its classification as substance causing skin sensitisation 1.

Glucaric acid



Substance Identity
IUPAC-Name: (2R,3S,4S,5S)-2,3,4,5-Tetrahydroxyhexanedioic acid
CAS No.: 87-73-0
Mass: 210,14 g mol $^{-1}$
Molecular Formula: $C_6H_{10}O_8$

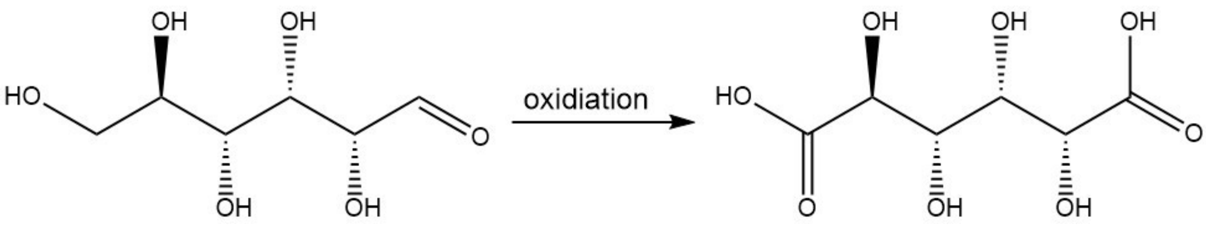
Classifications:
Harmonised: -
Notified: Eye Dam. 1, Flam. Sol. 2, Skin Corr. 1A

Registration: -

PACT: -

Regulatory Obligations (beside REACH/CLP):
Red Flags: -
Orange Flags: -

Feedstock: Glucose
Production:



Relevance:

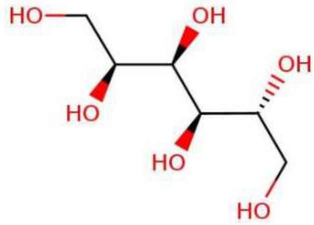
Patents: 1

Book/Review: Cell factories for biosynthesis of D-glucaric acid: a fusion of static and dynamic strategies, Junping Zhou et al., 2024, DOI: 10.1007/s11274-024-04097-6 [387]

Sci Finder References: 21
Sci Finder Reactions: Reactant: 43; Reagent: 0

Glucaric acid is a diacid mentioned as potential platform chemical in the DOEs report [22] with no registered manufacture/import in the EU. Commonly used industrial production methods are oxidation of glucose using nitric acid or using heterogeneous catalysts for a selective oxidation of glucose in two steps. The latter method is considered to be environmentally and economically more sustainable, but the stability of the used catalysts is still an issue [388]. Most commonly, researchers examine Au and Pt based catalysts in basic media (KOH or NaOH) [389-391]. As basic conditions can lead to C-C bond breaking, oxidation in non-basic media [390, 392] as well as photocatalytic systems [393-395] have been examined. Electrocatalytic methods have also been explored with varying degrees of success in selectivity and yield [396-398]. Biotechnological methods mainly involve recombinant *Escherichia coli* or *Saccharomyces cerevisiae* utilizing glucose as a feedstock [399-401]. Overall, most research on glucaric acid production has focused on glucose sources not containing impurities, which are commonly found in biorefinery feedstocks and are important factors in cost of production [402]. Glucaric acid could be applied in the synthesis of adipic acid (another platform molecule), but also in pharmaceuticals and direct applications exist [403]. No data on the share of bio-based production of glucaric acid was found. The only production pathways found in the literature were based on biomass. As there is no production or import registered within the EU, the amount of data is limited, but based on the available notified classifications there is no reason for a future categorization as SVHC, MHC or SOC.

Sorbitol



Substance Identity
IUPAC-Name: Hexane-1,2,3,4,5,6-hexol
CAS No.: 50-70-4
Mass: 182,17 g mol $^{-1}$
Molecular Formula: $C_6H_{14}O_6$

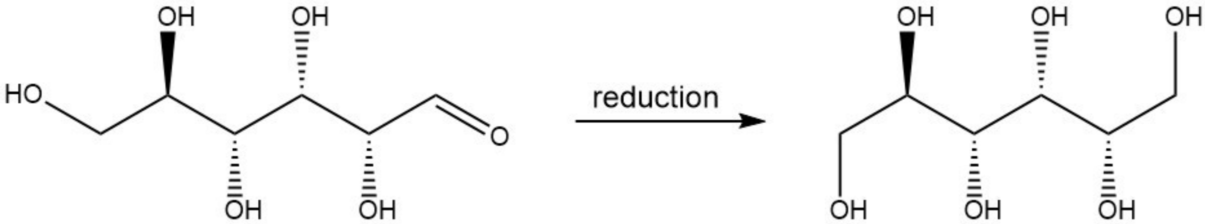
Classifications:
Harmonised: -
Notified: Not Classified

Registration: -

PACT: -

Regulatory Obligations (beside REACH/CLP):
Red Flags: -
Orange Flags: Food Contact Recycled Plastic Materials and Articles Regulation-repealed, Food Contact Regenerated Cellulose Directive, Plastic Materials and Articles Regulation, Recycled Plastic Food Contact Materials

Feedstock: Glucose
Production:



Relevance:

Patents: 8

Book/Review: The preparation of sorbitol and its application in polyurethane: a review, Jiacheng Xang et al., 2022, DOI: 10.1007/s00289-021-03639-4 [404]

Sci Finder References: 87
Sci Finder Reactions: Reactant: 2746; Reagent: 256

Sorbitol is another polyol mentioned as potential platform chemical in the DOEs report [22] which has not been registered for production/import in the EU. It is produced by catalytic hydrogenation of glucose [405], but more methods utilizing cellulose directly in one-pot synthesis are being developed [406]. Methods for direct cellulose utilization for sorbitol production often include ball-milling as pre-treatment, or during catalysis in the presence of Ru/AC catalyst [135], heterogeneous catalysis in sub-critical water [407], or transition metal catalysts in ionic liquids to increase the solubility of cellulose [408]. Recently researchers explored thermotolerant *Zymomonas mobilis* to produce sorbitol from sugarcane bagasse as a viable and sustainable strategy based on utilizing by-products and requiring less cooling than other strains [409-411]. Sorbitol can be used as pre-cursor for ascorbic acid, isosorbide and bioplastics [412]. No data on the share of bio-based production of sorbitol was found. The only production pathways found in the literature were based on biomass. As there is no production or import registered within the EU, the amount of data is limited, but based on the available notified classifications there is no reason for a future categorization as SVHC, MHC or SOC.

Are all platform chemicals green?

As for the evaluation if the surveyed platform chemicals are green, it is worth noting that all substances found in the literature called "platform chemicals" have at least one proposed synthetic pathway based on renewable resources and therefore fulfil at least one of the twelve principles of green chemistry.
As for the intrinsic hazards of the chemicals, only seven of them have harmonised CMR classification and can therefore be possibly categorised as SVHC, but none of them is on the candidates list yet. Even when looking at notified classifications from manufacturers/importers, only 18 show classifications based on which a SVHC categorization could be applied if those were harmonised. The 8 substances with harmonised and 30 with notified classifications fulfilling the conditions for MHC categorization might potentially be phased out in the future with exemptions for essential use. Based on the notified classifications (including those with harmonised classifications) 65 substances may fall under the SOC category in the future.
The question if all the platform chemicals surveyed deserve the adjective "green" cannot be fully answered based only on the feedstocks and the intrinsic hazards of the substances themselves. To evaluate if future green chemistry can be based on the listed chemicals, researchers need to make a deep analysis of the actual production processes (including energy consumption, greenhouse gas emissions, etc.) and products they will be used for, considering all green chemistry principles. Furthermore, potential data gaps for a more comprehensive hazard assessment need to be assessed and ideally filled.

7.2. Platform chemicals regulatory status

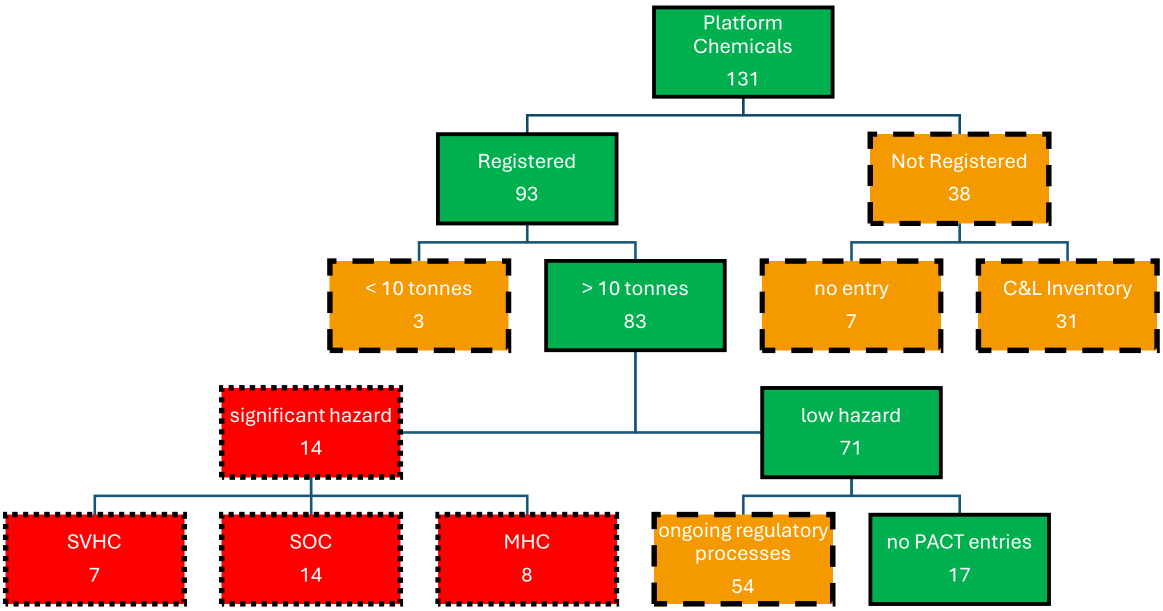


Figure 5 - Overview of the analysis of the identified green platform chemicals with respect to their regulatory status. Green boxes with full outline symbolize potential greenness. Orange boxes with interrupted lines symbolize not enough or inconclusive data for evaluation. Red boxes with dotted lines symbolize significant hazards.

Figure 5 provides an overview of the analysis of the identified green platform chemicals with respect to their regulatory status.

It is remarkable that the huge majority of the 131 identified platform chemicals are produced as bulk chemicals in a volume of more than 1 ton per year in the EU. 93 substances have been registered under REACH either as full registrations (87) or as intermediates only (6). Only 7 substances seem to be on the European market in amounts of less than 1 t/y or not at all and have only been pre-registered to the European Chemicals Agency (ECHA).

As Table 5 demonstrates, some of the platform chemicals occur on the European market in significant high volumes, notably the four platform chemicals ethanol, ethylene, methanol and propylene, which have reported production volumes of more than 10 million tonnes per year, and further 11 substances which have reported volumes between 1 and 10 million tonnes per year. These figures show that many platform chemicals are not new or unknown chemicals for the chemical industry but are already now being manufactured or imported and used in Europe in quite significant volumes. Furthermore, the four mentioned substances are key building blocks of the chemical industry, and only one (methanol) is considered of significant hazard according to ECHAs database.

Given that 66 % of the surveyed green platform chemicals are registered, we are in the favourable situation to have potentially significant information on the properties and uses pattern of many identified GPCs. 63 % of all GPC have been registered in tonnages above 10 t/a, indicating that these chemicals can be regarded as data rich as comprehensive data requirements are defined under REACH. Looking at the hazardous properties of these compounds, 17 % can be categorised on the basis of current data, as fulfilling SVHC, MHC or SOC criteria. It is noted that, of these categories, the SOC classification is the by far most comprehensive one. Substances which are registered in > 10t/a and not falling under these hazard-based categories can presently presumed as being of low (eco)toxicity and thus, represent high potential candidates for becoming substitutes for SVHC substances. Of course, their hazard status still needs to be confirmed, taking into account that new classification criteria for relevant properties (ED, PBT, vPvB, PMT, vPvM) have only recently been published [14]. 79 % are listed in the PACT, meaning that further assessment under REACH or CLP has either been already concluded or is in progress. Therefore, further data generation, (re)assessment of available data or risk management can be expected for some of them.

The seven platform chemicals with a potential future identification as SVHC under REACH based on their harmonised classifications are 1,3-butadiene (CAS: 106-99-0), benzene (CAS: 71-43-2), catechol (CAS: 120-80-9), isoprene (CAS: 78-79-5), carbon monoxide (CAS: 630-08-0), acetaldehyde (CAS: 75-07-0) and ethylene oxide (CAS: 75-21-8). They are (apart from isoprene) all produced at a volume above 1 000 tonnes per year in the EU and showing their high significance in the chemical industry currently. The exploration of potential alternatives for them is therefore of high importance as further risk management based on the current regulatory framework is probable. As the properties leading to a potential categorization as a SVHC include the properties for a potential categorization as MHC and SOC, phasing out and other measurements might be applicable.

Substances not covered by ECHA's public database

Nearly all platform chemicals mentioned in the literature were found in ECHA's public database. The ones not found are not part of the exemptions of Annex IV and Annex V of the REACH regulation [4], but are pre-registered or produced in a volume of less than a ton per year. The platform chemicals only pre-registered within ECHAs database are also rarely mentioned in the literature, for example 5-hydroxyvaleric acid (CAS: 13392-69-3, 100 reactions as reactant) generated 539 hits (without the inclusion of keywords) on SciFinder (accessed 21.11.2024). An even smaller number of papers deal with the synthesis of the substance [413-416]. Similarly to that, the other 6 substances seem to have only small relevance as industrial chemicals: Arabitol (CAS: 2152-56-9, 24 reactions as reactant), xylonic acid (CAS: 17828-56-7, 5 reactions as reactant), 3-acetoamido-5-acetylfuran (CAS: 95598-28-0, 79 reactions as reactant), 2-methoxy-5-methyl-thiophene (CAS: 31053-55-1, 11 reactions as reactant), muconic acid (CAS: 505-70-4, 91 reactions as reactant) and glutaconic acid (CAS: 1724-02-3). As for the small interest of researchers into these substances as reactants, it is of no surprise that companies also do not produce them or only in volumes below 1 ton per year in the EU.

8. Conclusion

A comprehensive list of chemicals has been compiled based on a general definition of platform chemicals to evaluate their potential and hazards based on publicly available information. This included their identity, their classification according to the CLP regulation, their manufacturing/import volumes in the EU and public processes within the regulatory framework of the EU. Furthermore, their possible categorization as SVHC, MHC and SOC has been evaluated. The most relevant substances based on production volume, number of search engine hits, number of reactions as reactants, number of patents and inclusion in the DOEs report on platform chemicals have been discussed in further detail. All the compiled data is made publicly available within the data repository of TU Wien for future research [240]. The data surveyed in ECHA's public database is summarised in a spreadsheet and can be searched and filtered.

The topic of green platform chemicals produced from biomass is an extensively researched one, which has led to not only potential or planned substitutions for petrochemical production methods but were actually implemented in several cases. Some of the discussed substances are already produced on industrial scale in sustainable ways and act as the main building blocks for today's chemical industry. As the focus of this work was to compile a list of green platform chemicals and survey the already reported hazards about them, the need for further critical research in both their sustainability and their (eco-)toxicity is evident. To avoid mistakes of the last century, the full life cycle of these chemicals must be considered. The list can and should be a starting point for further research into hazards, processes and derived products of platform chemicals.

The need for the replacement of fossil feedstocks such as coal, gas and oil is evident and has been discussed by many scientists. Biomass utilisation is an important measure to be taken but will not replace all fossil-based chemicals [7, 417, 418]. Many reagents and primary chemicals (e.g. ammonia) will not be replaceable by green platform chemicals, as they are not necessarily integrated into the structure but help modifying it. As GPCs are mostly bigger and more functionalized than current building blocks used, they might help reducing the demand for reagents which cannot be produced from renewable or currently recycled from waste. This main advantage of GPCs should be utilized in production as well as in development of new chemical products.

For the moment, many of the chemicals selected in this study may be considered as simple drop-in solutions, changing only the feedstock but not the chemical process and spectrum of end products. While such an on-spot substitution may have the immediate positive effect to replace a potentially more harmful petroleum based raw material, it does not necessarily transform the whole manufacturing process to a greener and more sustainable production scheme. Many chemicals derived from biological materials carry functional groups which make them attractive for further synthesis in contrast to petroleum-based raw materials which have to be functionalized. These resources would allow for more innovative developments in chemical industry utilizing them for alternative reaction routes. It is therefore recommended that GPCs should be investigated more comprehensively in academia to explore potentially alternative reaction routes and products for their economic utilization.

As positive as the impact of fermentative production of ethanol from corn was as a substitute for fossil fuels, switching the dependency from a single resource to another single feedstock (be it a regrow able one) is not necessarily sustainable and environmentally friendly. Whichever biomass is used to replace fossil feedstock, should be either from waste streams or be grown without putting additional burden on the ecosystems [419]. The research into more sustainable feedstocks for this purpose is very important, not only for bioethanol synthesis but for all biomass derived chemicals. The utilisation of fungal biomass as feedstock is rarely discussed in the literature concerned with platform chemicals, but chitin could be potentially used to produce N-heterocycles and other nitrogen containing compounds. Other saccharides such as fucoidan containing sulphur should also be explored, as many commodity and speciality chemicals contain heteroatoms other than nitrogen and oxygen [179].

This work has been a first attempt to systematically explore GPCs and evaluate their intrinsic hazards to human health and the environment. It is hoped that this inspires further research into the topic to open up more opportunities for industry to enable them to make the essential changes necessary for the green transition.

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