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Review

A Systematic Review of Syngas Bioconversion to Value-Added Products from 2012 to 2022

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Abstract: Synthesis gas (syngas) fermentation is a biological carbon fixation process through which carboxydotrophic acetogenic bacteria convert CO, CO_2, and H_2 into platform chemicals. To obtain an accurate overview of the syngas fermentation research and innovation from 2012 to 2022, a systematic search was performed on Web of Science and The Lens, focusing on academic publications and patents that were published or granted during this period. Overall, the research focus was centered on process optimization, the genetic manipulation of microorganisms, and bioreactor design, in order to increase the plethora of fermentation products and expand their possible applications. Most of the published research was initially funded and developed in the United States of America. However, over the years, European countries have become the major contributors to syngas fermentation research, followed by China. Syngas fermentation seems to be developing at "two-speeds", with a small number of companies controlling the technology that is needed for large-scale applications, while academia still focuses on low technology readiness level (TRL) research. This systematic review also showed that the fermentation of raw syngas, the effects of syngas impurities on acetogen viability and product distribution, and the process integration of gasification and fermentation are currently underdeveloped research topics, in which an investment is needed to achieve technological breakthroughs.

Keywords: synthesis gas; syngas fermentation; carboxylic acids; alcohols; Web of Science; The Lens

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1. Introduction

The pressing global concerns over atmospheric carbon dioxide (CO_2) levels, climate change, and waste recycling have served as major incentives to pursuing commodities that are derived from alternative non-fossil raw materials. The escalating urgency of these issues has spurred researchers to explore both established and emerging carbon sequestration technologies to meet the demand for carbon-based fuels and chemicals, while drastically reducing the emissions from fossil-derived sources [1]. These challenges are in line with the United Nations Sustainable Development Goals (UNSDG) for 2030, namely the Sustainable Cities and Communities (Goal 11), Responsible Production and Consumption (Goal 12), and Climate Change mitigation (Goal 13) [2].

A way to comply with this demand is through the reutilization of carbon that is trapped in hard-to-treat residues. This can be accomplished by the application of thermochemical technologies, such as gasification and pyrolysis, that facilitate the conversion of recalcitrant and heterogeneous forms of residual carbon, such as those that are contained in municipal solid waste (MSW) or lignocellulosic waste biomass, into simpler forms, as in the case of synthesis gas or syngas [3,4]. This gaseous product is mainly composed of carbon monoxide (CO), CO_2, and hydrogen (H_2), but can also contain, in lower amounts, methane (CH_4), short chain hydrocarbons (C_nH_m), hydrogen sulfide (H_2S), ammonia (NH_3), and hydrogen cyanide (HCN). Syngas can be easily transformed into heat and power by direct burning, but it can also be converted to liquid fuels, traditionally through the Fischer–Tropsch process (FTP) [5,6]. FTP is a catalytic process that converts a mixture of H_2 and CO into aliphatic products. However, like many other catalytic processes, it presents several downsides. Notably, it requires high energy inputs, due to the high temperature and pressure that are required to kickstart the reactions, and expensive rare metal catalysts composed of critical raw materials, which tend to become easily fouled with the contaminants that are present in the syngas [6,7].

Syngas fermentation can be the biological alternative to FTP. It consists of the use of microorganisms, which are designated carboxydotrophic acetogens, to assimilate the gaseous carbon forms, i.e., CO and CO_2, in the absence of oxygen (O_2), converting them into microbial biomass, carboxylic acids, and alcohols that can be used as platform chemicals, or as feedstock for liquid fuel production [8,9]. This conversion can be performed in a wide range of pressures and temperatures, since there are strains of acetogens that grow under mild conditions, normally at 37 °C, while others thrive in thermophilic environments, growing at temperatures higher than 50 °C [9]. Syngas fermentation is not only applicable to syngas itself, but virtually to any gaseous mixture that is composed mainly of CO, CO_2, and H_2, such as industrial off-gases from steel mills, including Linz–Donawitz gas, and the cement industry [10–13].

Research on syngas fermentation goes as far back as the 1970s, but has seen an exponential increase in interest from 2008 onward, nowadays being a promising research field for bioenergy and climate action [6,14]. Over the years, there have been a multitude of review publications on the subject, focusing on different approaches, such as revealing the most promising mesophilic and thermophilic microbial catalysts, bioreactor configurations that facilitate the gas–liquid mass transfer and increase the carbon fixation yields, genetic manipulation to develop more robust acetogens or to support the specific metabolic pathways that increase the product yield, or the optimization of the fermentation parameters for a more efficient bioconversion process [7,15–18]. In 2022, Calvo et al., performed a much-needed systematic review of the research into syngas fermentation, yet their focus was on scientific publications and collaborations, pointing towards the most fruitful areas of publication and future collaborative research interests [6]. However, none of these reviews performed a holistic, integrated evaluation between research and final application.

The end goal of research and innovation is to gain knowledge, to improve our understanding of the universe, and to allow for the progress of society. However, knowledge by itself has little value; it is only through sharing that it can fulfill its role. This is mainly achieved through scientific publications and intellectual property (IP) protection via patent applications, both of which facilitate innovation and improve knowledge [19]. This review aims to fill this information gap by crossing the data from both scientific and patent databases. Taking into consideration the particular case of syngas fermentation, a series of questions concerning the advances from 2012 to 2022 were addressed:

- What is being researched in syngas fermentation and what are the differences to what is being patented?
- Which value-added product(s) resulting from syngas fermentation is/are the main focus of this research?
- Has syngas fermentation technology been commercialized? What is the TRL of the research vs. implementation?
- What should be the main focus of syngas fermentation scientific research going forward?

Having these questions in mind, the objective of this systematic review was to obtain a thorough overview of the research and patent publications from 1 January 2012 to 31 December 2022 in the field of syngas fermentation. This work aims to understand the real development level of the research on syngas fermentation and its technological advances, pointing not only to the immediate research needs and bottlenecks, but also targeting the interaction between academia and industry to identify opportunities for innovation and investment.

2. Materials and Methods

A systematic search methodology was followed, as represented in Figure 1, based on the method that was developed by Calvo et al., 2022 [6], using two databases: the Web of Science™ (WoS) (www.webofscience.com/, accessed on 5 March 2023) for the scientific publications and The Lens (LENS) (www.lens.org/, accessed on 5 March 2023) for the patent publications. From the datasets that were obtained, Bibliometrix and Microsoft® Excel® were used to categorize the research papers and patent publications over the 2012 to 2022 period [20]. The entries for the scientific publications were then sorted by topic, product focus, and the funding country of origin, while patents were sorted by jurisdiction, leading assignees with the highest number of patents published, and leading owners.

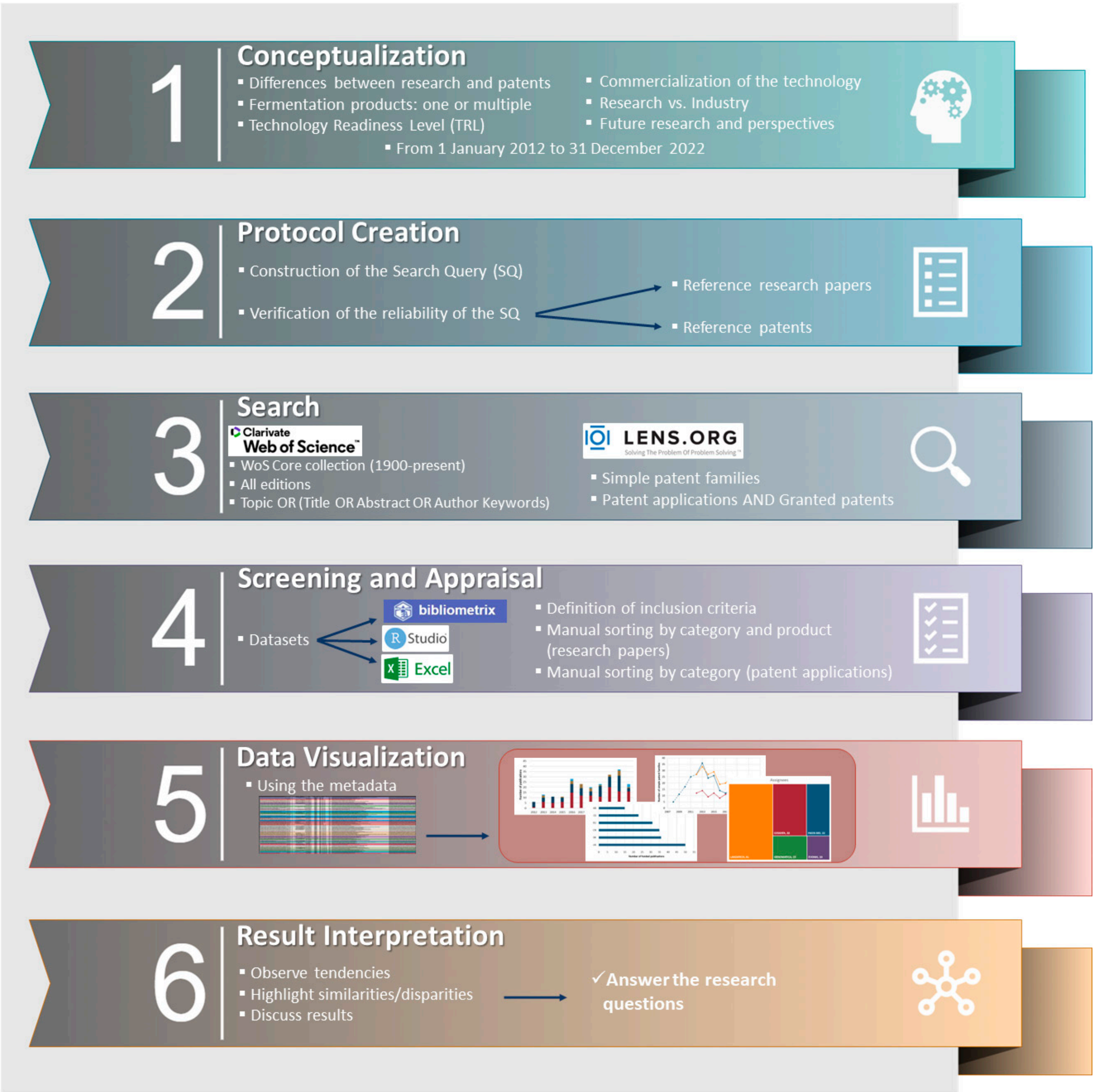

Figure 1. Flowchart of the systematic search methodology followed for the systematic review of syngas bioconversion to value-added products.

2.1. Databases and Search Query

To obtain an accurate overview of the scientific publications and patents that were written in English from 1 January 2012 to 31 December 2022, WoS and LENS were chosen as the search engines for the systematic review. The Web of Science Core Collection (1900-present) database, with all of its available editions, was used for the WoS search engine. The search was performed by "Topic" (title, abstract, author keywords, and Keywords Plus) OR "Title OR Abstract OR Author keywords". This search method was adopted because many reference publications on syngas fermentation were left out when only the search by "Topic" was performed, including life cycle assessment/techno-economic analysis (LCA/TEA) publications and some important reviews. The datasets that were obtained from the WoS were downloaded in BibTeX format and fed to bibliometrix, which is an R-Tool for comprehensive science mapping analyses [20] through biblioshiny [21] in RStudio ver. 2022.07.1+554 open-source software [22]. The data on the number of researchers (in full-time equivalent) per million inhabitants were obtained from UNESCO [23], and the total annual number of publications was obtained from the WoS Core Collection in all topics, by searching "PY = year" (from 2012 to 2022).

In the LENS database, the search was filtered by simple patent families and document type, focusing on patent applications and granted patents. Simple patent families are a collection of patent documents that are considered to cover a single invention. This allows for a simplified overview of a group of patents with the same priorities and the same technical content, facilitating data screening.

The use of a simple search query (SQ), namely "(syngas fermentation) OR (synthesis gas fermentation)", in LENS resulted in a reliable number of relevant results. However, the same search in the WoS resulted in data with many off-topic publications, while other publications of interest were absent. As such, an augmented SQ model, drawing inspiration from the one that was employed by Calvo et al., (2022) was implemented, and is provided for reference in Appendix A.

It was necessary to include not only the word syngas, but also all the possible variations that represent syngas, such as gas components, producer gas, and synthesis gas. Additionally, it was crucial to exclude not only products that were obtained from the catalysis of syngas, but also the FTP processing of syngas. Finally, "NOT ((. . .) "syngas from" OR "synthesis gas from")" was also removed from the query, as some publications that used raw syngas from various sources, like syngas from the industry, were excluded.

2.2. Data Screening and Visualization

To facilitate the data screening and outlier exclusion, namely the publications or patents that did not have syngas fermentation as their main focus, the datasets were converted to .csv files for easy manipulation and validation in Excel® (Microsoft® Excel® for Microsoft 365 MSO ver. 2209 Build 16. 0. 15629. 20200). The publications and patents were verified and categorized manually, through title, abstract, and claim verification. Several inclusion criteria were selected in order to normalize the data screening, as follows:

Criterion 1: A fermentation process using a gaseous carbon source that is composed of CO or CO_2+H_2, or a mixture of the three.

Criterion 2: The utilization of acetogenic microorganisms, mixed cultures of acetogenic microorganisms, or mixed cultures of acetogenic microorganisms with other types of microorganisms + *Criterion 1*.

Criterion 3: The production of acids, alcohols, or a mixture of both + Criterion 1.

Criterion 4: The genetic modification of microorganisms to optimize and/or increase syngas conversion and/or the metabolite production from syngas.

2.2.1. Research Publications

Biblioshiny enabled the distribution of publications by year, funding institution, and document type. Publications were automatically sorted by: book chapter—research article, book chapter—review, conference proceedings—research article, conference proceedings—

review, and research article and review, based on the information that was contained in the metadata [21]. The publications that were retrieved from the dataset were further divided into 10 different topics based on defined classification rules, as follows:

Bioreactor design: Publications that included "bioreactor", "continuous fermentation", "batch", "reactor", or "bubble column" in the title. Publications that referred to the performance of "fermentation in bioreactor", or that used a physical support for the biocatalyst, such as nanoparticles or biochar, in the definition of the "objective of the work" that was included in the abstract.

Raw syngas: Publications that included "producer gas", "furnace gas", "industrial", or "biomass-derived" in the title. Publications that referred to the utilization of syngas from industrial or thermochemical processes in the abstract.

Culture medium optimization: Publications that included "medium" or "supplement" in the title. Publications that referred to the supplementation of components into the culture medium in the definition of the "objective of the work" that was included in the abstract.

LCA/TEA: Publications that included "life cycle assessment", "techno-environmental assessment", "sustainability assessment", "techno-economical assessment", or "financial assessment" in the title. Publications that referred the performance of a "life cycle assessment", "sustainability analysis and/or assessment", "emission analysis and/or assessment", or a "techno-economical assessment" in the definition of the "objective of the work" that was included in the abstract.

Modeling: Publications that included "modeling/model", "simulation", or "algorithm" in the title. Publications that referred to the performance of a "predicting model" or "simulation" in the definition of the "objective of the work" that was included in the abstract.

Molecular biology: Publications that included "engineered", "mutation/mutagenesis", "expression", "gene replacement", "genome and/or genomic", or "metabolic engineering" in the title. Publications that referred to the performance of the genetic manipulation, manipulation of pathways or enzymes, the development of engineered acetogenic strains, or a description of the pathways and/or novel enzymes in the definition of the "objective of the work" that was included in the abstract.

New analytical techniques: Publications that included "technique" or "method" in the title. Publications that referred to the performance of an analysis using a new sensor or a new analytical technique in the definition of the "objective of the work" that was included in the abstract.

New microorganisms: Publications that included "novel" or "new" before the word "acetogen", or before the genus and species name of a microorganism. Publications that referred to the description of new syngas-converting microorganisms in the definition of the "objective of the work" that was included in the abstract.

Process optimization: Publications that included "improvement", "production", "formation", "effect", "tolerance", "integration", "optimization", or "enhanced" in the title. Publications that referred to the performance of a process optimization or integration in the definition of the "objective of the work" that was included in the abstract.

Review: Publications that were bibliographic or process reviews. Publications that compared technologies.

The publications in the dataset were also sorted by the main product of the syngas fermentation, in a total of 19 different categories: *Acetate and Acetic acid*, *Acetone*, *Butyrate and Butyric acid*, *Butanol*, *Isobutanol*, *2,3-butanediol*, *Ethanol*, *Ethylene*, *Hexanoate and Hexanoic acid*, *Malate and Malic acid*, *Methane*, *Methanol*, *Mevalonate and Mevalonic acid*, *n-caproate and n-caproic acid*, *n-caprylate and n-caprylic acid*, *Poly-3-hidroxibutyrate*, *Propionate and Propionic acid*, *Isopropanol,* and *Succinate and Succinic acid*. The publications that focused on combinations of products, e.g., mixtures of acids, mixtures of alcohols, or mixtures of acids and alcohols, were categorized as "multiple". The TRL of the scientific publications of the 5 leading publishing authors, and of the patents from the 2 leading inventors who also authored scientific publications, was assessed by an abstract and materials and methods screening, following the TRL definition of the European Commission [24].

2.2.2. Patents

A procedure similar to the one that was performed for the scientific publications was also carried out for the patents. The dataset that was returned by the SQ was thoroughly assessed to select only the patents that were related to or usable for syngas fermentation. Patents can have two statuses: published or granted. Granted patents hand the assignees a monopoly over the patented invention for a set timeframe. Published patent applications do not confer these rights to the assignees of the invention, but simply state that the patented invention might be protected in the future [25]. For this study, the filtered dataset was further sorted by publication year, grant year, the jurisdiction of the publication or grant, and by the 5 leading assignees with published and/or granted patents, for comparison. To provide a topic overview of the submitted patents, a classification into five topics was performed, using a methodology similar to the one that was followed for the scientific publications. The classification rules were as follows:

Genetic engineering: Patents that described genetically modified microorganisms or enzymes that performed/assisted with syngas/CO/CO_2+H_2 fermentation.

New microorganisms: Patents that described a novel syngas/CO/CO_2+H_2 fermenting microorganism.

Parts: Patents that described a part or object that could be used in a syngas/CO/CO_2+H_2 fermentation process.

Process: Patents that described a production process using syngas/CO/CO_2+H_2 fermentation with acetogenic microorganisms.

Product: Patents that described a product composition with one or more precursors that were obtained through syngas/CO/CO_2+H_2 fermentation with acetogenic microorganisms.

Multiple: Patents that described combinations of the previous topics.

The sorted scientific publications, patents, and TRL classification datasets can be found in the Supplementary Materials (File S1).

3. Results and Discussion

3.1. Scientific Publications

The SQ for the WoS search engine retrieved a total of 312 results, of which, 254 fit the selection criteria (see Section 2.2). The number of publications per year and the document types are summarized in Figure 2.

From 2012 to 2022, research articles represented the majority of the publications (with an average of 19.4 publications per year), followed by reviews (an average of 2.9 publications per year), conference proceedings (an average of 0.5 publications per year), and both types of book chapters (research articles and reviews), which were less represented, with averages of 0.2 and 0.1 publications per year, respectively. It is important to note that the number of conference proceedings publications is most likely underestimated, since only the WoS-indexed proceedings were accounted for. In addition, many conference publications might not have been written in English, which would also exclude them from the search. In the period that is under analysis, a significant increase in the number of publications was only observed from 2016 onwards. In fact, from 2012 to 2015, the number of yearly publications on the subject were few and varied only slightly in number, with a maximum of 15 results matching the search criteria in 2014 (Figure 2). The relevant publications in this period, i.e., those with the highest number of total citations, addressed the production of ethanol, butanol, and hexanol from syngas, the use of mixed cultures in membrane biofilm reactors, and the upgrading of ethanol to n-caproate [26–29]. Important reviews on syngas fermentation were also published by Bengelsdorf et al., in 2013, with 129 citations, and by Latif et al., in 2014, with 125 citations, providing an overview on the state of the art and showing the most promising syngas fermentation applications at the time [8,30].

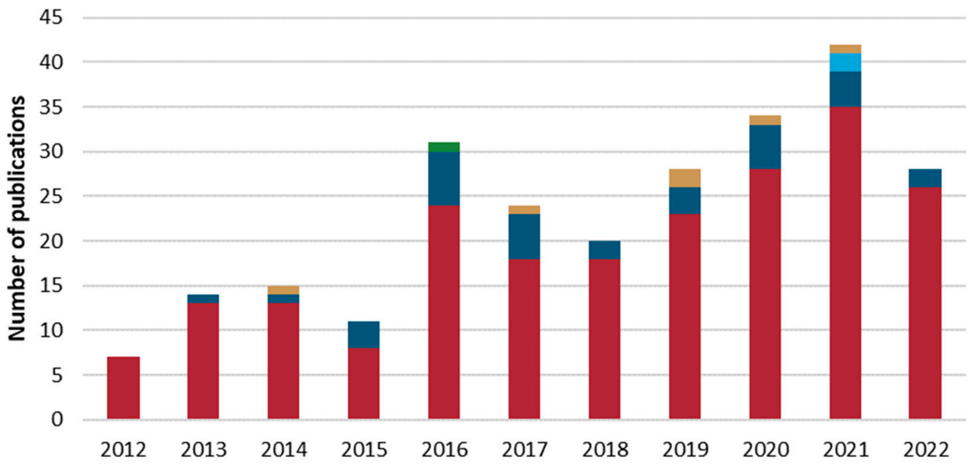

Figure 2. Number of scientific publications per year on the subject "syngas fermentation", sorted by document type, from 2012 to 2022. Color coding is as follows: ■ book chapter (research article); ■ book chapter (review); ■ conference proceedings (research article); ■ research article; ■ and review.

In 2016, the number of scientific publications doubled in value from 2014, reaching a new maximum of 31 publications, comprising research articles, reviews, and one research article that was published as book chapter. This suggests that, in 2016, the interest level for syngas fermentation technology increased, with the release of 24 original article publications, a value that was only achieved again in 2019. From 2016 onward, the number of yearly publications was considerably higher compared to the 2012 to 2015 period. Even in 2018, when the number of publications reached a lower point, with 20 publications, this was still 33% above the number that was reported for 2014 (Figure 2). From 2018 to 2021, the number of yearly publications kept increasing, with an average rate of 28% per year. In 2021, the year with the highest number of publications, a total of 42 publications were published, with 35 being original articles, 4 being reviews, 2 being reviews in book chapters, and 1 being a conference proceeding. The number of publications experienced a decrease of 33% in 2022 compared to the previous year, which had 28 publications. The publications in 2022 equaled the total of 2019 and corresponded to 26 original research articles and 2 reviews [31,32].

The evaluation of the number of publications that is presented in Figure 2 could be biased by two variables: the increasing number of researchers worldwide and the increasing number of total publications in the WoS Core Collection. Figure 3a,b shows the variation in the total number of publications in the WoS Core Collection, the number of researchers per million of the world's inhabitants, the number of yearly scientific publications that are related to "syngas fermentation", and their respective value per capita (considering researchers at a full-time equivalent) and per total publications in the WoS Core Collection during the analyzed period.

Within the analyzed period, the yearly increase in researchers per million inhabitants was rather constant (Figure 3a), occurring at an approximate rate of 2.8% per year. Similarly, from 2012 to 2021, the total number of publications in the WoS Core Collection increased approximately 4.8% per year, with 2015 having an increase of 15%. In 2022, for the first time within the analyzed period, there was a decrease in the number of total publications, to a value that was 14% lower than that of 2021. This deceleration in scientific production might be due to the COVID-19 pandemic and the lockdown measures that were applied during 2020 and 2021, with the temporary closure of research institutes all over the world and/or the conscription of laboratory equipment and research teams to respond to the pandemic emergency, with its effects only being felt in the subsequent years. From Figure 3b, it can be observed that the steady increase in the number of researchers and the variation in the number of publications over the analyzed period exerted little effect on the observed trend for the syngas fermentation publications. However, these variables might help to explain the periods of great variation in the data, as in the cases of 2015 and 2022. A more in-depth analysis of the yearly data seems to indicate that 2015 presented a lower number of publications regarding syngas fermentation, as decreases of 27% and 36% were registered in the number of syngas fermentation publications and the syngas fermentation publications per total publications, respectively, even though the total number of the publications in the WoS database increased in that year. As for 2022, while the total publications in the WoS Core Collection decreased by 14%, both the number of syngas fermentation publications and the number of syngas fermentation publications per total publications showed more substantial decreases of 33% and 23%, respectively. Compared to other research areas, these numbers reveal that syngas fermentation is still a niche field of research. The occurrence of interest peaks appears to be a common occurrence and might be related to intermittent funding incentives. However, the fact that there was a constantly growing trend in the syngas fermentation scientific publications over the analyzed time period ensures that this is a topic of interest and a focus for new research.

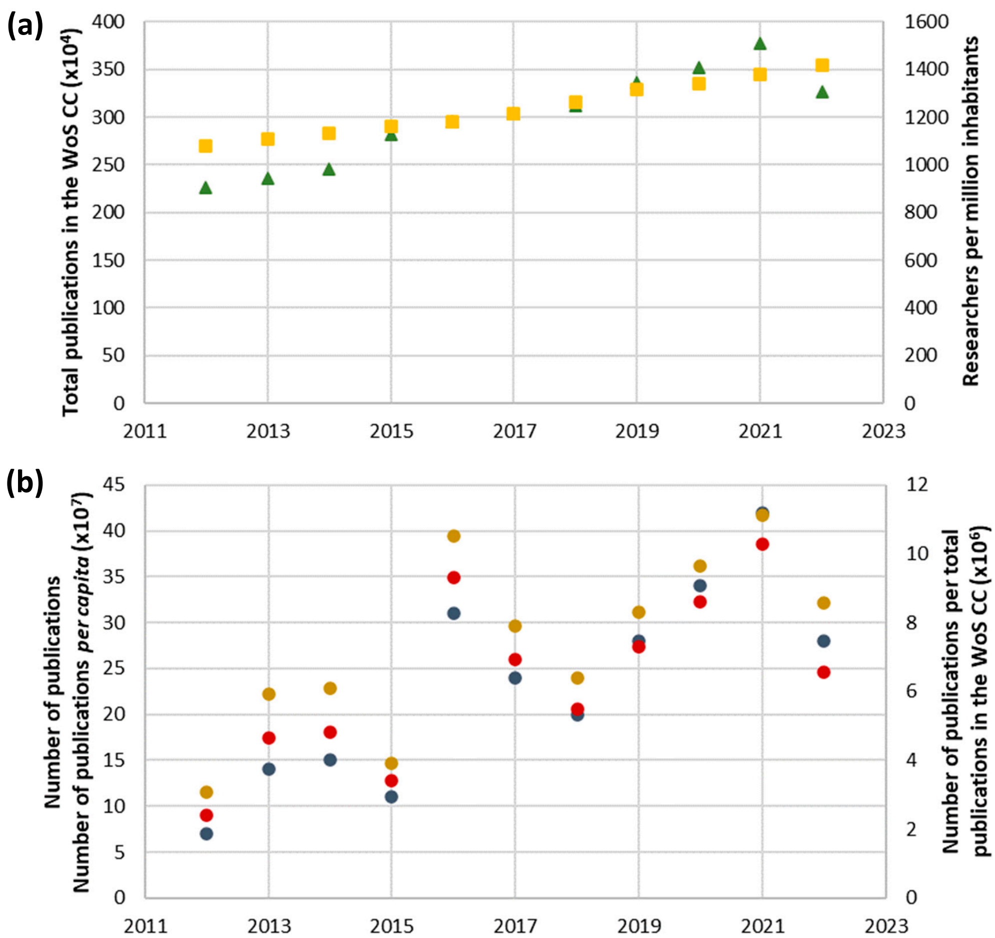

Figure 3. (**a**) Variation of the total number of publications in the WoS Core Collection and the number of researchers per million inhabitants in the world from 2012 to 2022, and (**b**) number of scientific publications per year related to "syngas fermentation" and its value per capita and per total publications in the WoS Core Collection. Color coding is as follows: (**a**) ■ number of researchers per million inhabitants; and ▲ total publications in the WoS Core Collection; and (**b**) ● number of scientific publications in "Syngas fermentation" (main *yy* axis); ● number of scientific publications in "Syngas fermentation" per capita (main *yy* axis); ● and number of scientific publications in "Syngas fermentation" per total publications in the WoS Core Collection (secondary *yy* axis).

In order to refine the information on the specific topics within the syngas fermentation research field along the studied period, the publications were categorized into different topics, according to the criteria that were previously selected (Section 2.2.1.). The relative percentages for each topic, considering the total publications per year to be 100%, are shown in Figure 4.

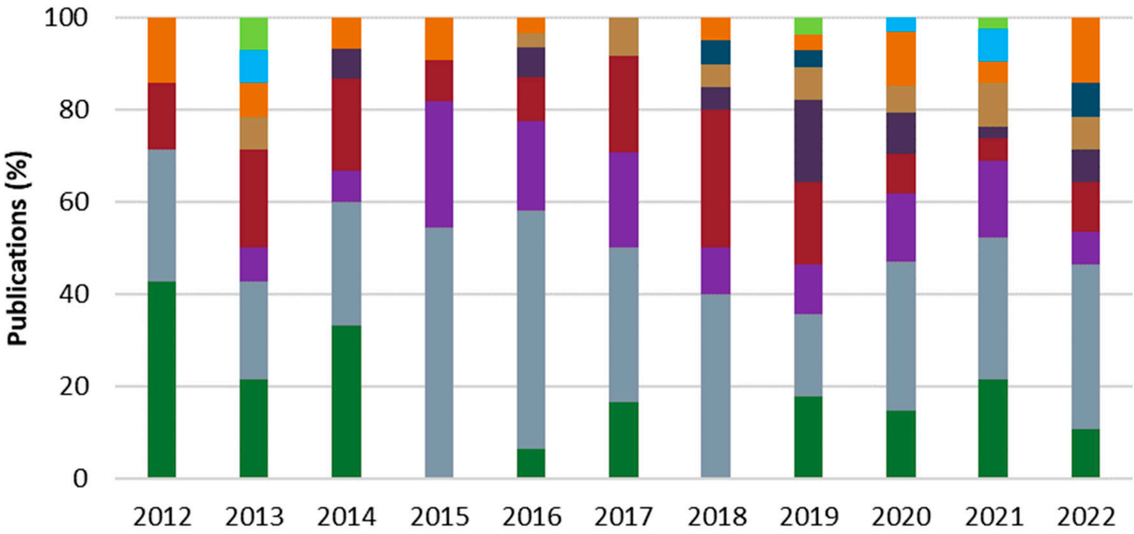

Figure 4. Distribution per year of the scientific publications about "syngas fermentation" sorted by topic, from 2012 to 2022. Color coding is as follows: ■ bioreactor design; ■ culture medium optimization; ■ LCA/TEA; ■modeling; ■ molecular biology; ■ new analytical techniques; ■ new microorganisms; ■ process optimization; ■ raw syngas; and ■ review.

Over the 2012–2022 period, not only was there an increase in the number of total publications, but there was also a diversification of the research topics. Process optimization was the most published topic, accounting for 34% of all the publications over the studied period, followed by molecular biology at 16%. The relevant publications on process optimization have focused mainly on the production of longer-chain products, such as n-caprylate, n-caproate, and hexanol, which are higher-value commodity chemicals when compared to shorter-chain products [28,33,34]. From 2012 to 2014, molecular biology played an important role in syngas fermentation research. An example of this is the scientific publications of Berzin et al., 2012 and 2013, and Köpke et al., 2014, on the development of recombinant strains for the selective production of non-traditional alcohols, such as acetone, butanol, and 2,3-butanediol [35–37]. During that 3-year period, researchers also focused on process optimization, as well as new bioreactor configurations that would allow for higher productivities and easy scalability [27,38,39]. An increase in scientific reviews was observed from 2015 onwards, which summarized the research that was performed, with a focus on the evaluation of the future technological and economic viability of syngas fermentation technology, and how it could be integrated into an industrial setting using biomass-derived syngas or industrial off-gases [40,41]. In 2016, the second most cited paper in the 2012–2022 period was published. This was a review of gas fermentation as a flexible platform for the commercial scale production of low carbon fuels and chemicals from waste and renewable feedstocks, by Liew et al., with 208 citations [15]. From 2016 onward, the publications that were related to process optimization presented the highest increase in the studied period, with 2.6 times more publications than in 2015. The publications on process optimization, which showed a slight growth tendency since 2012, increased visibly in 2015 and 2016, remaining the topic with the highest number of publications until the end of the studied period. In 2016, Marcellin et al., published the most cited research publication on process modeling, with 85 citations, where a systematic platform that allowed for the development of energy efficient pathways for the production of chemicals and advanced fuels via C1 fermentation, using complete omics technologies that were augmented with genetic tools and a genome-scale mathematical model, was presented [42].

From 2017 to 2019, the research focus shifted yet again to experiments on bioreactors, envisioning an easy scalability with the addition of novel support materials for the biocatalysts, such as biochar and nanoparticles, and new reactor configurations that would tackle one of the biggest limitations of these syngas fermentation processes, namely the gas–liquid mass transfer [43–47]. In 2018, a decrease in the overall publications was observed. However, the most cited publication in the studied period was from this year, a scientific paper by Haas et al., in Nature Catalysis (280 total citations) that focused on a solar-powered CO_2 and H_2O reduction to syngas, followed by its fermentation to alcohols [48]. Articles describing newly isolated syngas-fermenting microorganisms and strains appeared for the first time in 2018, reappearing in 2019 and 2022. This suggests that the search for more robust isolates capable of performing syngas fermentation and producing interesting new products was challenging, with only four publications in 11 years [49–52]. The desire to advance syngas fermentation to an implementable technology was substantiated by the highest number of publications on the subject being in 2020 and 2021. LCA/TEA analyses and studies using syngas impurities or raw syngas, i.e., the syngas from thermochemical processes and industrial off-gases, have tried to demonstrate the potential of this technology for the future production of biofuels and platform chemicals [11,12,53–61]. Research article publications with a focus on process optimization, including culture media optimization, process or genetic modeling, systems integration, and molecular biology, all saw a visible increase in these two years, with the publication of important studies, such as Heffernan et al., 2020 (process optimization), Nangle et al., 2020 (molecular biology), and Roy et al., 2021 (raw syngas) [61–63].

From 2012 to 2022, the research focus was also centered on the multiple value-added products that can be produced by syngas-fermenting microorganisms. Such products, mainly carboxylic acids and alcohols, are pivotal as platform chemicals for the reduction in fossil fuel use and to the energy transition effort. Figure 5 is a representation of the top four most referred to products that are obtained from syngas fermentation, which were sorted from the publications on the subject during the studied period, representing more than 90% of the total publications.

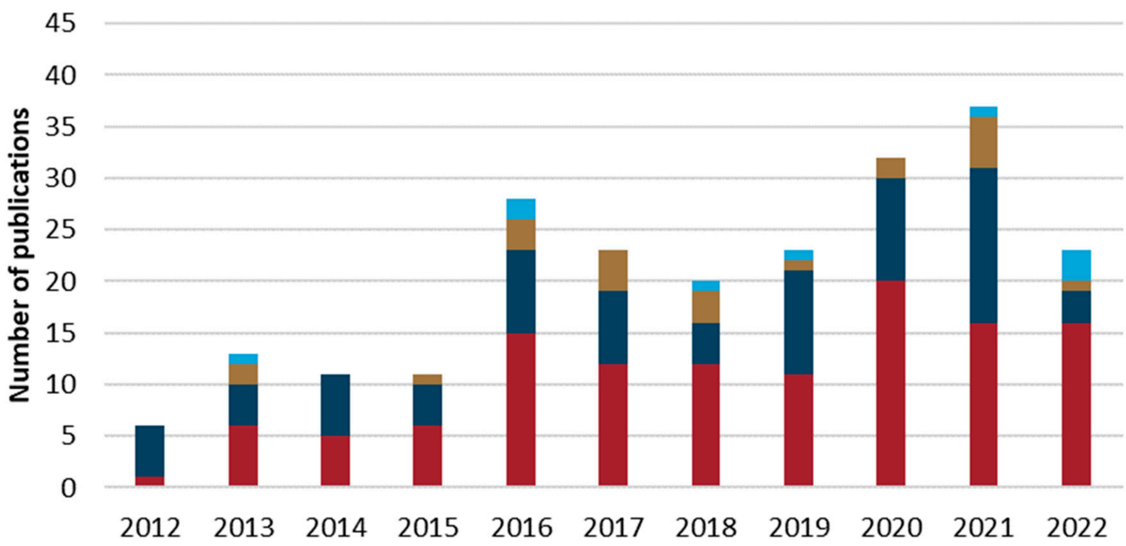

Figure 5. Scientific publications per year related to "syngas fermentation", sorted by top 5 value-added products produced from syngas, from 2012 to 2022. Color coding is as follows: ■ acetic acid; ■ butanol; ■ ethanol; and ■ multiple.

From 2012 to 2022, the research focused mainly on the production of multiple products from syngas fermentation. Combinations of different alcohols, such as ethanol, acetone, hexanol, propanol, and butanol or 2,3-butanediol, and carboxylic acids, such as acetic, butyric, propionic, n-caproic, n-caprylic, formic, malic, and mevalonic acids, and other value-added products, such as fatty acid methyl esters (FAMEs) or polyhydroxyalkanoates (PHAs), were the main focus of this research [64,65]. This reflects the effort to maximize the value that syngas fermentation could represent in the replacement of fossil-based chemicals and to increase the plasticity of a future syngas biorefinery [27,29,34,49]. The production of long-chain value-added products is a means of increasing carbon capture efficiency, especially in cases where it is coupled with other CO_2 capture technologies and a catalytic transformation to syngas [66]. In 2022 there seems to have been a shift of the research focus to the production of butanol [67–69], whereas the publications focusing on ethanol production were lowered considerably. This shift could be justified by the fact that butanol is considered to be an advanced biofuel that offers numerous advantages over ethanol. Specifically, it has a similar calorific value, octane value, and air–fuel ratio to gasoline, is less corrosive than ethanol, and can be transported through pipelines. Butanol is also immiscible with water (H_2O) and can be used pure or blended with gasoline, without requiring engine modifications [70]. Moreover, butanol can be upgraded to 2,3-butanediol, which is also utilized as a sustainable aviation fuel (SAF) with remarkable results [71].

During the analyzed period, the authors with the highest number of publications on syngas fermentation were Kennes C. and Veiga M.C. from the University of A Coruña, with 16 publications [68], followed by Atiyeh H.K. from Ohio State University, with 14 publications [72], and Angenent L.T. from the University of Tübingen and Weuster-Botz D. from the Technical University of Munich, with 10 research articles each [73,74]. An analysis of the research conducted by these authors revealed that the leading research on syngas fermentation was mainly focused on TRL 2 and 3, with only one publication by Pardo-Planas O. and Atiyeh H.K., among others, modeling a TRL 7 installation using the data from TRL 3 assays [75].

In order to comply with ever-restricting emission regulations and mitigate climate change, governments around the world have been actively funding research into alternative biotechnological processes for the production of sustainable biofuels, or for reducing or cutting emissions, creating funding programs and packages specifically for this purpose. The funding information that was present in the dataset was evaluated in terms of its country or region of origin. Funded publications represented 91% of the total published works, 228 out of 250, and among these, 31 publications were supported by private funding, such as business angels, family and friends, private companies, or foundations. The analyzed publications were funded by the national funds of 25 different countries and the European Union (EU). A distinction was established depending on the origin of the funding. Communitarian funds were classified as EU, whereas national funds were categorized as the individual country, regardless of whether they originated from an EU member state. The results for the six countries or regions with the highest number of funded contributions (above 10 publications) are presented in Figure 6.

The United States of America (US) holds the highest number of funded publications, with a total of 50 in the analyzed dataset. Germany was also a major contributor to this syngas fermentation research, with 36 publications, of which 23 were funded by national funds from the German Federal Ministry of Education and Research, 8 with national funds in collaboration with private companies and foundations, and only 5 were funded by joint national and EU funds. Germany had its highest numbers of outputs in 2016 and 2022, with seven funded publications. China was a relatively recent contributor to the syngas fermentation research field, with a total of 35 funded publications during the studied period, reaching its highest number of publications in 2020.

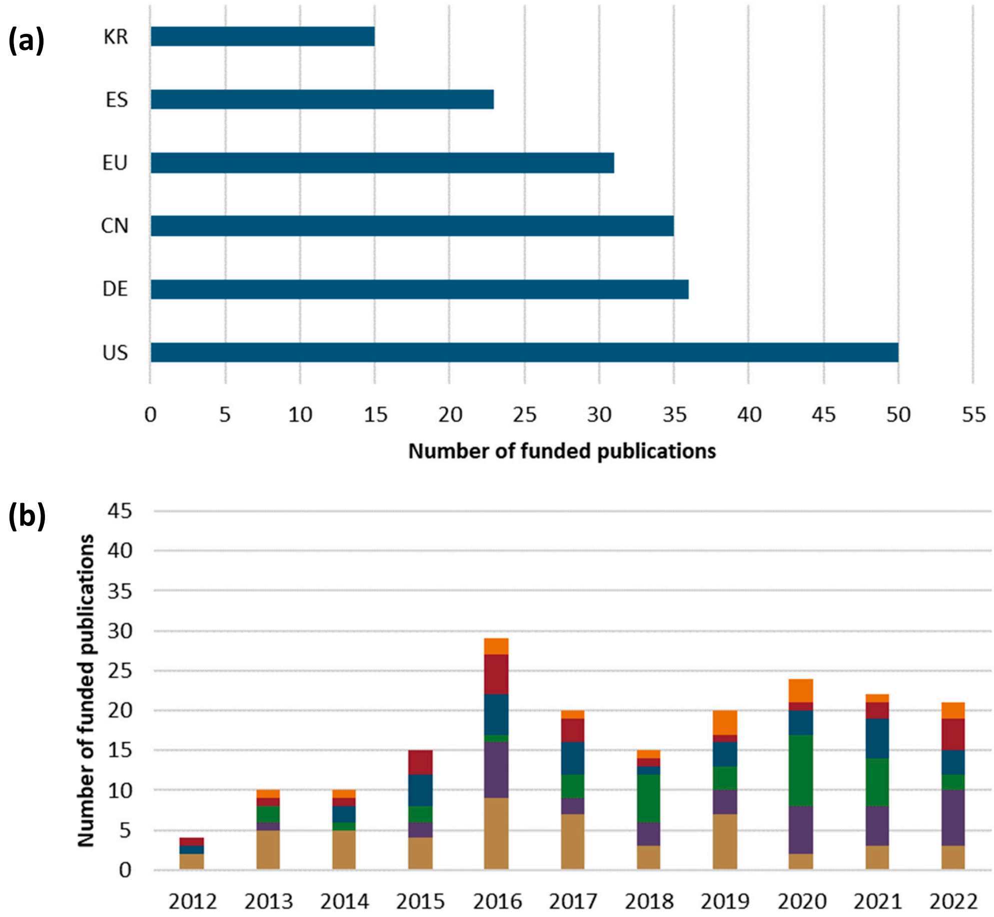

Figure 6. (**a**) Number of funded scientific publications per funding institution's country or region from 2012 to 2022, and (**b**) number of scientific publications funded per year per funding institution's country or region. Color coding is as follows: ■ Republic of Korea (KR); ■ Spain (ES); ■ European Union (EU); ■ China (CN); ■ Germany (DE); and ■ United States of America (US).

A total of 31 publications acknowledged the funding of EU communitarian funds. The highest number of publications that were funded by the EU was achieved in 2016 and 2021, coinciding with the years when European projects like SYNPOL (Biopolymers from syngas fermentation—2012 to 2016, [76]), SYNTOBU (Biological production of butanol from syngas—2013 to 2017, [77]), AMBITION (Advanced biofuel production with energy system integration—2016 to 2019, [78]), and BIOCONCO$_2$ (BIOtechnological processes based on microbial platforms for the CONversion of CO_2 from the iron and steel industry into commodities for chemicals and plastics—2018 to 2022, [79]) passed their midterm or were near their ending date. Spain appeared as the fifth-largest investor in syngas fermentation, with 23 funded publications, 4 of which were funded solely by the Spanish Ministry of Economy and Innovation or by regional governments. Spain and the US were the only countries that had publications every year in the analyzed period.

The Republic of Korea has funded 15 publications on syngas fermentation, mainly through the C1 gas refinery program [80]. This program was funded by the National Research Foundation of Korea and the Ministry of Education, Science and Technology in 2015, focusing on the development of core C1 gas refinery technologies with the economic feasibility to decrease the fossil fuel dependency of Korean industries [81]. Accordingly, a substantial increase in the number of scientific publications that were funded by the Republic of Korea was observed since 2016, with the highest number of these funded publications being achieved in 2019 and 2020.

In terms of external collaborations, Germany had the highest number of collaborations with countries and companies that were outside of Europe, with eight co-publications with partners from various countries such as Australia, Canada, Brazil, and the US. The countries with the fewest collaborations were China and the Republic of Korea, both with only one publication that was in collaboration with another country or private company. The publications that were funded by EU communitarian funds tended to rely on collaborations, mainly with countries from within the EU or from the European Economic Area, such as Norway, for example.

3.2. Patents

The SQ that was used in LENS returned a dataset with 345 simple patent families, from which 249 were selected as being related to or appliable within syngas fermentation. Of these, 103 were granted and 88 are currently active. Figure 7 shows the distribution of the simple patent families by filing, publishing, and granting year (Figure 7a) and their distribution by topic (Figure 7b).

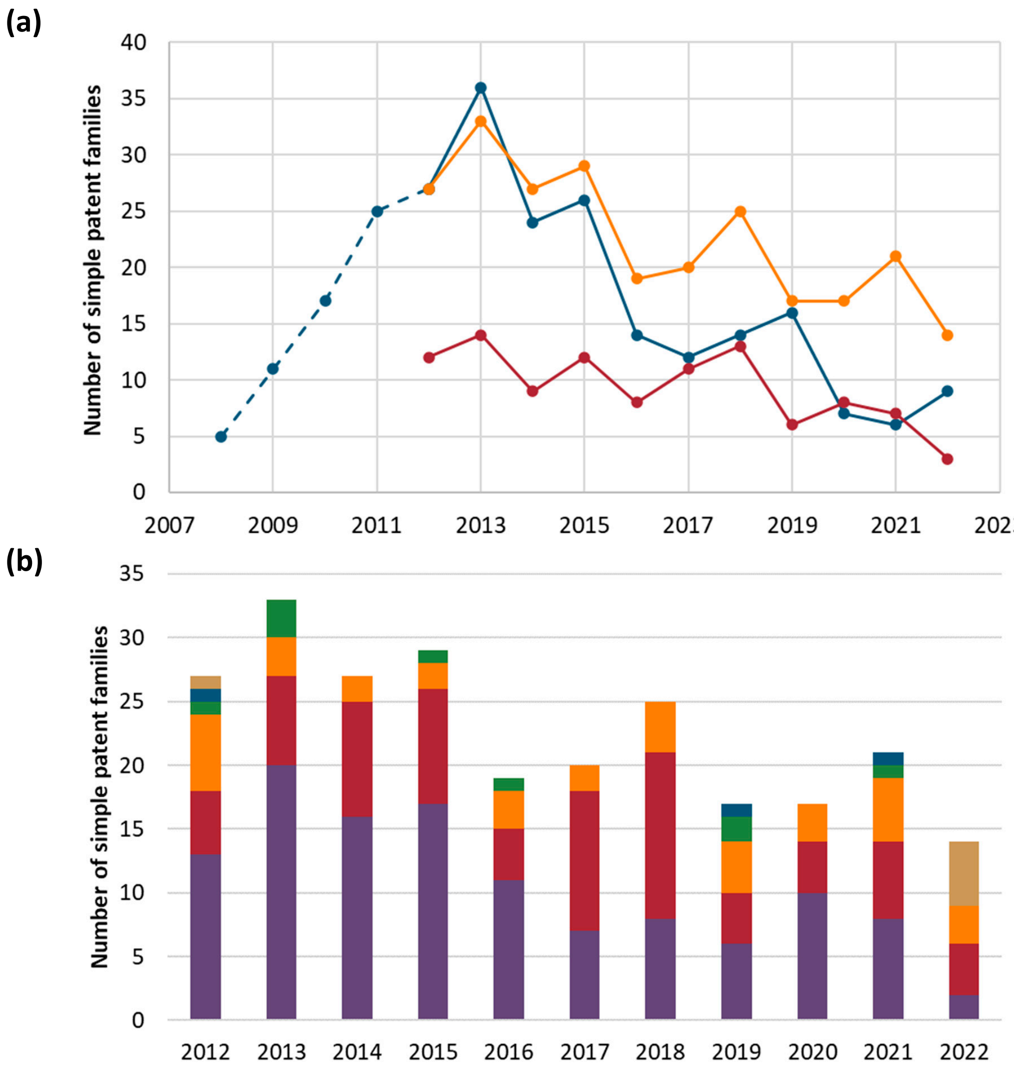

Figure 7. (**a**) Number of simple patent families filed, published and granted from 2012 to 2022, and (**b**) number of simple patent families from 2012 to 2022, organized by topic. Color coding is as follows: (**a**) – ● – filed before 2012; —●— filed after 2012; —●— granted; and —●— published; and (**b**) ■ genetic engineering; ■ multiple; ■ new microorganisms; ■ parts; ■ process; and ■ products.

From the data presented in Figure 7a, it can be seen that there was a growing trend in the patent filing related to syngas fermentation until 2013, with a maximum of 36 filed patents. However, a decrease in this patent filing occurred from 2013 onwards, with occasional peaks in 2015 and 2019. It is important to note that this decline in patent filing over the analyzed period may have been a result of underestimation, due to the delay between the filing and publication dates. While the average time between the patent filing and the publication varies between 18 months to 3 years, this actual time frame can vary widely depending on several factors, including the jurisdiction in which the patent was filed, the complexity of the invention, and the level of scrutiny that is required to assess the patent application. Filing information is only publicly available after publication, and the publishing process can take several years, as can be seen from the patents that were published during the analyzed period and those that had filing dates prior to 2012, going back to 2008. Nonetheless, it is observable that 2013 was indeed a year of technological progress in syngas fermentation, with 33 published patents. The year with the highest number of granted patents was 2018, with an increase of 63% compared to 2016.

The topic that was related to the syngas fermentation process had the highest representation, with 118 patents being published. The years of 2013 and 2015 saw the highest number of patents describing different syngas fermentation processes, with 20 and 17 patents, respectively. The patents describing multiple topics, namely combinations of these syngas fermentation processes with descriptions of parts, such as novel bioreactors or propeller shapes, or with new and/or engineered microorganisms, were the second most frequent type of published patent among the 249 patents that were analyzed, with 76 published patents and a peak of 13 patents in 2018. Genetic engineering was also an important patent topic, with 37 patent applications, while parts, product descriptions, and new syngas-fermenting microorganisms appeared with 9, 6, and 3 patent applications, respectively. Process-focused patents had their publishing peak between 2012 and 2016. Between 2017 and 2018, the inventors' focus seemed to have shifted to multiple-topic patents. The highest number of patents focusing on genetic engineering for the production of novel products with acetogenic microorganisms occurred in 2012, but this topic has been a constant focus during the period that was studied, with at least two patents published every year. Parts, products, and new syngas-fermenting microorganisms were sporadic topics, with patents about product composition appearing more prominently in 2022.

In order to access the global distribution of these syngas fermentation patents, the dataset was organized by jurisdiction, i.e., the country, territory, or organization of the patent publishing or granting. Figure 8 shows the results that were obtained for each jurisdiction, organized by patent topic.

From Figure 8, it is possible to observe that the US published the highest number of patents on syngas fermentation, 216, followed by the World Intellectual Property Organization (WO) with 189 patents. China (CN) and Europe (EP) were in the third and fourth positions, with similar numbers of published patents, 140 and 139, respectively. Canada, South Korea, Japan, Brazil, and Australia published 105, 86, 83, 80, and 76 patents, respectively. The remaining countries had less than 50 published patents between 2012 and 2022, with some having as few as 1 published patent. The US, CN, and EP jurisdictions are often preferred by assignees due to their large market potential, strong legal systems with strong IP enforcement, efficient patent offices, and easy access to innovation, while WO allows for a time saving, cost-effective option for achieving protection in multiple countries, justifying the increased patent publication values under these jurisdictions [82].

Thematically, the process-related patents were the majority within most jurisdictions, followed by multiple thematic patents and genetic engineering. The multiple thematic patents described either the apparatus and methods for the cultivation of microorganisms with syngas (under the topics "parts + process") or novel and/or engineered microorganisms and cultivation methods with syngas (under the topics "new microorganisms and/or genetic engineering + process"). The patents that were related to parts and new microorganisms were most common in the 12 leading publishing jurisdictions, while the product-related patents were exclusive to the US and WO jurisdictions.

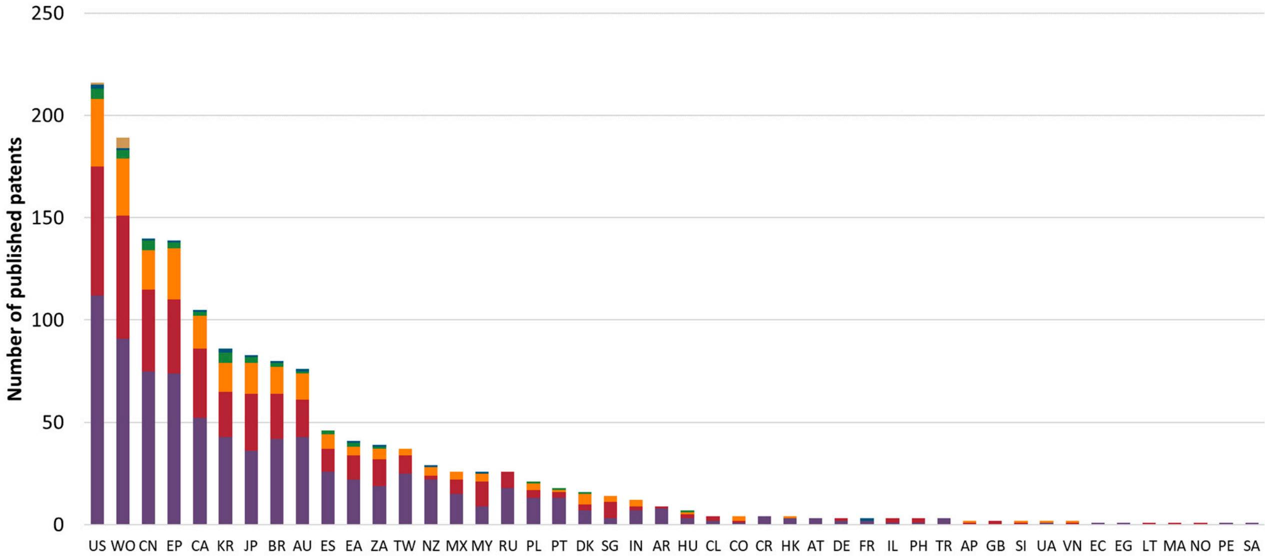

Figure 8. Number of patents related to syngas fermentation published between 2012 and 2022 by jurisdiction and sorted by topic. Color coding is as follows: ■ genetic engineering; ■ multiple; ■ new microorganisms; ■ parts; ■ process; and ■ products. Country or organization abbreviation is as follows: WO—World Intellectual Property Organization; EP—European Union Intellectual Property Office; EA—Eurasian Patent Organization; and AP—African Regional Intellectual Property Organization; the remaining country coding is set by the Alpha-2 (ISO 3166) code.

Patents can be submitted by either individual assignees, universities, or companies as a means of protecting IP. Patents are especially important for companies, since they are proof of a company's innovative strength, facilitating their product marketing and investor/capital attraction. From the dataset, the five leading assignees with the highest number of patents published were selected, namely Lanzatech, Coskata, Genomatica, Ineos Bio, and Evonik, representing 56% of the total published patents. This top five was composed in its entirety by companies that performed syngas fermentation to bioethanol or to other products of interest, such as 1,2-butanediol and 2-hydroxyisobutyric acid, showing the influence of bioenergy in the syngas fermentation field. Figure 9a,b depicts the number of patents published, the leading patent owners, and the yearly distribution by the topic of the patents that were published by the top companies.

During the 2012–2022 period, five companies appeared as the leading investors/patent assignees in syngas fermentation technologies: LanzaTech, Coskata, INEOS Bio, Evonik, and Genomatica (Figure 9a).

LanzaTech was the company with the highest number of published patents and is currently the only fully successful company to commercialize its gas fermentation technologies. The company was founded in 2005 in New Zealand and moved their headquarters to the US soon after. Since then, it has been investing in gas fermentation, first to ethanol, and now to a multitude of platform chemicals that are used to make products such as PolyEthylene Terephthalate (PET) bottles [81]. The company has commercial plants that are fully operating from steel mill gases in China, India, and Belgium, and many more that are scheduled for construction all over the world in the next few years, using not only steel mill gases as feedstock, but also gasification–fermentation integrated technologies for the use of different types of biomasses, such as MSW and agricultural residues [16]. Over the last 11 years, the company has been applying for patents on a regular basis, with five patents being published in 2022. LanzaTech's syngas fermentation patents were mainly related to genetic engineering and process methodology.

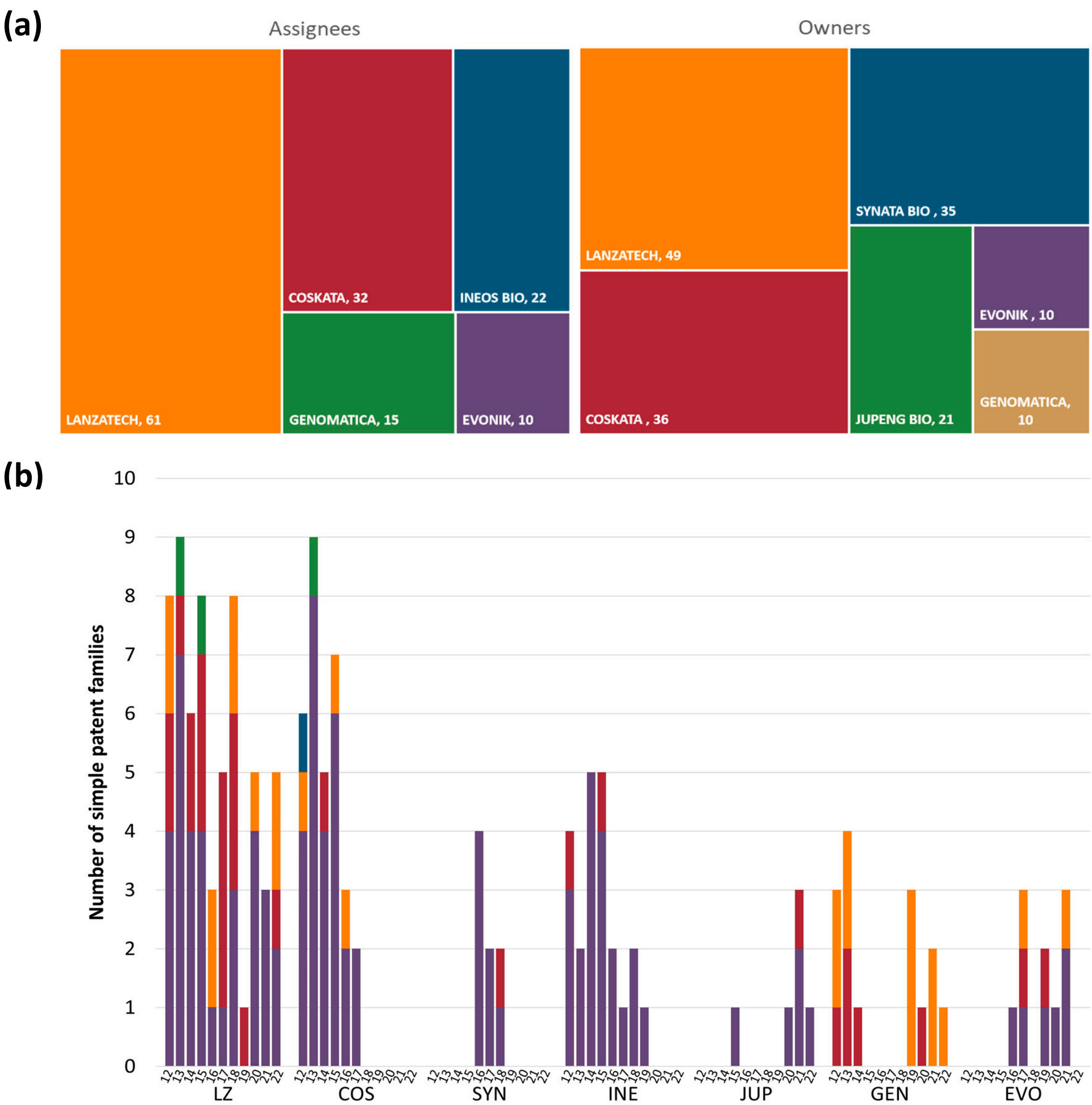

Figure 9. (**a**) Number of simple patent families published by the 5 leading assignees (left) and 6 leading patent owners (right), and (**b**) number of patents published by the 7 leading assignees from 2012 to 2022, sorted by topic. Color coding is as follows: (**b**) ■ genetic engineering; ■ multiple; ■ new microorganisms; ■ parts; and ■ process. LZ—LanzaTech; COS—Coskata; SYN—Synata Bio; INE—INEOS Bio; JUP—Jupeng Bio; GEN—Genomatica; and EVO—Evonik.

Coskata appeared as the second most important patent publisher and holder. However, as shown in Figure 9b, these patents were published only from 2012 to 2016. Coskata declared bankruptcy in 2015, and its technology was bought that year by Synata Bio, a company that is still active nowadays, having published patents that were related to syngas fermentation until 2018 [83]. It focused mainly on single-step, feedstock-flexible fermentation processes that converted syngas through fermentation into ethanol. In 2016, Synata Bio bought the Hugoton (Kansas, US) cellulosic ethanol plant from the bankrupt company Abengoa, adapting it for the fermentation of syngas to ethanol; however, it was not able to keep the plant operational, selling it in 2021 [84]. Nowadays, Synata Bio focuses on cellulosic bioethanol production, having reconverted their syngas-fermenting pilot plants to that end.

INEOS Bio, the third-biggest patent holder within the analyzed period, was a branch of the multinational chemicals manufacturer INEOS, which was focused on the production of advanced biofuels. The company published several patents at a constant rate until 2019 and was the proprietor of a semi-commercial plant in Vero Beach (Florida, US), which produced bioethanol at a commercial level from MSW syngas. However, in 2016, the plants that were owned by INEOS Bio were put on sale and the company was bought by Jupeng Bio. Jupeng Bio, another bioenergy company, is the proprietor of an integrated gasification and fermentation process that was demonstrated at the pilot level in 2017 [85]. The company published patents that were related to syngas fermentation in 2020 and 2021, namely the design of parts and process description.

Much like INEOS Bio, Evonik is a company that is focused on specialty chemicals and is based in Germany. This company uses syngas to produce 2-hydroxyisobutyric acid and other value-added platform chemicals. In 2020, in partnership with Siemens, it commissioned a pilot plant to convert H_2O and CO_2 into CO and H_2, which could be converted into value-added products by the Evonik fermenters in Marl, Germany. Evonik's patents focused on process description and the development of genetically engineered microorganisms for the production of various molecules, such as acetone, N-acetyl homoserine, or diverse alcohols.

Finally, Genomatica is a US company that is focused on replacing fossil-based chemicals with more sustainable building blocks, particularly on the production of 2,3-butanediol from sugarcane. Its portfolio of syngas fermentation patents is mainly composed of the genetic engineering of syngas-fermenting microorganisms for the production of isobutanol, aniline, and other valuable platform chemicals, although it does not actively produce them from syngas fermentation.

During the analyzed period, LanzaTech appeared as the dominant company in terms of patent publishing and ownership, accounting for 25% and 20% of the total published patents, respectively. From Figure 9b, it is possible to observe that LanzaTech was the only company that was consistently publishing patents during the analyzed period. The company mainly focused on the syngas fermentation process, including microbial cultivation methods, the production of multiple products of interest, and patents that were related to the genetic engineering of syngas-fermenting microorganisms and enzyme optimization. From 2012 to 2016, Coskata emerged as LanzaTech's most direct competitor, owning and publishing patents that were related to process description, genetic engineering, and multiple topics. Furthermore, it was granted a patent for a novel syngas-fermenting clostridium strain, *Clostridium coskatii*, in 2012, which is still in force at the time of this study. Synata Bio published some patents with Coskata during 2016 and 2017, but their interest in syngas fermentation seemed to wane after 2018. INEOS Bio was the third-biggest contributor to the syngas fermentation patents, with 22 patents being published from 2012 to 2019. Ineos Bio patents mainly focused on process description and process and apparatus description for a syngas fermentation to ethylene. Jupeng Bio appeared as one of the largest patent owners in this study, albeit with inconsistent patent publishing, with one patent published in 2015 and the remaining patents being published in the last three years of this study, indicating the relative novelty in the syngas fermentation market. Genomatica also published inconsistently during the analyzed period, having a hiatus between 2015 and 2018. The patents that were published by Genomatica mainly focused on the genetic engineering of syngas-fermenting strains for the production of multiple platform chemicals, their maintenance, and their product separation processes. As for Evonik, they have been publishing patents that are centered on process description, genetic engineering, and multiple topics since 2016.

3.3. Overview

In analyzing the results that were obtained in this systematic review, it was possible to observe an inverse trend between the scientific and patent publications from 2012 to 2022. The years 2013, 2016, and 2021 were especially relevant, as these were years of increased scientific and patent publications, indicating a possible technological breakthrough. Patent filing related to syngas fermentation saw a fast-paced increase from 2005 to 2013 (as can be verified by a quick search on LENS), much as was observed for syngas fermentation scientific publications [6]. The years of 2012 and 2013 marked the installation and first runs of many of the pilot plants that have operated over the last 11 years, and companies started to develop optimized processes and strains [7]. However, only in 2016 did the syngas fermentation research field see a turn from articles with a focus on fundamental science to articles with a more industrial and commercial point of view. LCA and TEA evaluations of this technology also started to appear more frequently from 2016 onward, most probably fed with data from the pilot and demonstration facilities that were active at the time [7,16,18,31]. As for 2020 and 2021, it was possible to observe the resurgence of scientific publications that were related to raw syngas fermentation, and the study of the effects of syngas impurities, such as HCN and H_2S, which tend to hinder fermentation, lowering the process productivity [10–12,60,61,86,87]. This is a recent topic in syngas fermentation research, with only seven publications appearing during the studied period. However, research using raw syngas is of utmost importance, since some of the active syngas fermentation plants from the analyzed period were forcibly closed due to tar and syngas impurity accumulations, leading to "catastrophic" decreases in their production [7,88].

Another important observation from the obtained data is that the research tended to focus on the production of multiple products with long carbon chains from syngas fermentation. Research on the production of longer-chain value-added products is important, not only to maximize carbon fixation, but also in the transition from a long to a short carbon cycle economy. With a large product portfolio, the greater the chances are of increasing the versatility of the biorefinery, which could also be coupled with genetic engineering tools to optimize the productivities and customize the microorganism towards the customer's interest. LanzaTech is an example of a company with a large portfolio of these high-income products, that already have guaranteed partnerships with brands such as Danone, L'Oréal, or Zara, beyond the traditional bioethanol and SAF market [89].

In terms of the most contributing countries for syngas fermentation research, the US had the highest number of funded publications (Figure 6a) and the highest number of published patents (Figure 8). Except for LanzaTech (which was founded in New Zealand, but soon after moved its headquarters to the US) and Evonik, all the other five leading companies were founded in the US at the turn of the millennium, many by acquiring technology from the pioneering researchers in the gas fermentation field from several US universities at the time. However, from 2015 for the EU, and from 2017 for China, an increase in the investments into syngas fermentation research was observed, achieving higher publication levels than those from the US later in the time span (2020 and 2021). The enforcement of the EU Green Deal, the climate law, the push for stricter climate targets for 2030, the war between Russia and Ukraine, and the Chinese pollution crisis might be some of the reasons for such a sudden interest increase in these carbon mitigation technologies, which not only severely cut emissions, but also add value with the co-production of biofuels and bio-based chemicals that can help to substitute fossil-based ones [90]. Funding programs such as the C1 gas refinery program of KR and EU projects such as SYNPOL, AMBITION, BIOCONCO$_2$, and PYROCO$_2$ are examples of the investment from the world's governmental entities into syngas fermentation research [76,78–80,91]. The decrease in the number of Chinese publications in 2022 might be related to the strict COVID-19 policies that have been enforced, with China being one of the most affected countries in the world by the pandemic.

From the results that were obtained, it appears that syngas fermentation, as a technology, is developing at two different speeds. From 2012 to 2022, the research mainly focused on low TRLs, namely TRL 2 and 3. However, by crossing the data on the research authors and patent inventors, it was observed that the leading inventors co-authored a relatively high number of scientific publications. Köpke M. and Simpson S.D. (LanzaTech) were the inventors of 23 patents that are owned by LanzaTech and the co-authors of 9 research publications. Most publications that were authored by Köpke and Simpson are considered to have a TRL of 2 or 3, but both inventors co-authored an LCA research paper with data from LanzaTech's first pilot plant (TRL 7). As stated before, scientific publications with the fermentation of raw syngas or a focus on the effect of the impurities that are present in raw syngas have only recently been released. Researchers have tended to focus mainly on productivity increases, the effects of the different gaseous components on the product distribution, and how to tackle the inherent mass transfer challenges, but not on how to fully integrate gasification and fermentation in a more efficient, economically viable way [60,87]. On the other hand, LanzaTech is actively commercializing its technology, giving actual proof that it works with variable feedstocks and that it can be an added value for any carbon-producing industry, succeeding where several other companies of the same branch have failed.

This disparity between research and industry might be due to the resources and investments that are required for the construction and maintenance of a gasification and fermentation pilot plant. A large consortium with industrial partners and constant investment would be necessary to take the syngas fermentation technology from the bench scale research to higher TRLs, and this might be hard to achieve in the current socio-economical conjuncture. There are operational difficulties related to the syngas flow regulation between the gas source and fermentation vessel, and scale adjustments are required in order to fully integrate syngas fermentation into higher-TRL facilities, which might be hard to achieve without prior testing and optimization [3,7,16,92]. Furthermore, the most advanced research into syngas fermentation, belonging to the US, was bought by private companies, who tend to protect innovation through industrial secrets and not fully disclose their research. This has resulted in an observable decrease in US-funded publications in recent years, but not necessarily in patent publications, opening the way for competitors such as the EU and China to occupy the lead in novel syngas fermentation research and contribute to this “two-speed” phenomenon.

4. Conclusions

The relatively low number of patents and publications that have tackled syngas fermentation in the period of 2012 to 2022 reveals that this is still a niche research topic. In this review, the following research questions were answered:

- What is being researched in syngas fermentation and what are the differences to what is being patented?
- Initially, the research focus was centered on the genetic manipulation of microorganisms and most published research was funded/developed by the United States of America. Over the years, the research focus changed to process optimization, and European countries became the biggest contributors in terms of the number of publications. In terms of patent publications, five companies stood out, namely LanzaTech, Coskata, INEOS Bio, Genomatika, and Evonik. These companies published 56% of the total analyzed dataset of simple patent families, focusing on process description, the genetic engineering of syngas-fermenting microorganisms, and multiple-topic patents, i.e., patents that described combinations of these topics.
- Which value-added product(s) resulting from syngas fermentation is/are the main focus of the research?
- Ethanol was the most studied solo product, followed by acetic acid and butanol. The production of multiple fermentation products was the main focus of the research over the studied period. The production of multiple products is a way of increasing the applicability and plasticity of a future syngas biorefinery. However, the companies tended to focus mainly on the production of bioethanol from syngas, while the production of other alcohols or value-added products were a minority in the company’s product portfolios, due to the inherent complexity that is associated with culturing engineered microorganisms.
- Has this syngas fermentation technology been commercialized? What is the TRL of the research vs. the implementation?
- LanzaTech was the only company that was able to achieve the commercialization of its syngas fermentation technology. It owns several demonstration and pilot plants in

the US and China, and, in collaboration with the steel mill industry, has been able to sell several of these industrial facilities based on carbon capture for producing value-added products from syngas. These facilities can be adapted to consume the escaped gases from virtually any CO_2-emitting industry. The most recent of such ventures was the ArcelorMittal plant in Ghent, Belgium, which was launched in December 2022.

- The research on syngas fermentation focused mainly on low TRLs, between TRL 2 and TRL 3, while the companies operated at a TRL of 7 to 9. This is an indicator of a "two-speed" development between academia and industry. While a small number of companies based in the United States of America control the technology that is required for the large-scale application of syngas fermentation, academia is still focusing on low TRL research. This can be related, on the one hand, to the necessity for novelty or achievable disruption in the actual pool of knowledge, which can be easily achieved in small-scale assays, or, on the other hand, with the large investments that are necessary for large-scale infrastructures and operations, which are not easily accessible to research groups.
- What should be the main focus of syngas fermentation scientific research going forward?
- The focus of syngas fermentation research should be centered on raw syngas fermentation, the evaluation of syngas impurity effects on acetogens, and the process integration of gasification and fermentation technologies. Furthermore, in order to increase the carbon capture efficiency and further facilitate the transition from fossil fuels, the production of long-chain value-added products should be the focus of future research. Ideally, it would be necessary to transform syngas fermentation into a flexible and versatile technology that is applicable to any carbon-rich off-gas, offering a close to complete carbon fixation into products. These are topics that seem to lack research and such thematics are pivotal to advancing these syngas fermentation technologies to a more mature level.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en16073241/s1, File S1: Scientific publication and patent datasets used in this systematic review.

Author Contributions: Conceptualization, M.P., P.M. and C.S.; methodology, M.P. and C.S.; validation, M.P., P.M. and C.S.; formal analysis, M.P.; data curation, M.P.; writing—original draft preparation, M.P.; writing—review and editing, M.P., P.M. and C.S.; supervision, P.M. and C.S.; funding acquisition, P.M. and C.S. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Appendix A

The search query that was used in this study was: ((TS = ((((syngas OR "synthesis gas" OR "producer gas" OR C1 OR "H2 and CO") NEAR/2 (convers * OR ferment * OR metabol *)) AND ((formate OR acet * OR propion * OR butyr * OR valer * OR capro * OR capryl * OR acid$ OR ethanol OR butanol OR propanol OR pentanol OR hexanol OR octanol OR alcohol$ OR chemical$) NEAR/2 (production OR synthesis))) NOT ("Fischer-tropsch synthesis" OR cataly * OR "CO hydrogenation"))) OR (TI = ((((syngas OR "synthesis gas" OR "producer gas" OR C1 OR "H2 and CO") NEAR/2 (convers * OR ferment * OR metabol *)) AND ((formate OR acet * OR propion * OR butyr * OR valer * OR capro * OR capryl

* OR acid$ OR ethanol OR butanol OR propanol OR pentanol OR hexanol OR octanol OR alcohol$ OR chemical$) NEAR/2 (production OR synthesis))) NOT ("Fischer-tropsch synthesis" OR cataly * OR "CO hydrogenation"))) OR (AB = ((((syngas OR "synthesis gas" OR "producer gas" OR C1 OR "H2 and CO") NEAR/2 (convers * OR ferment * OR metabol *)) AND ((formate OR acet * OR propion * OR butyr * OR valer * OR capro * OR capryl * OR acid$ OR ethanol OR butanol OR propanol OR pentanol OR hexanol OR octanol OR alcohol$ OR chemical$) NEAR/2 (production OR synthesis))) NOT ("Fischer-tropsch synthesis" OR cataly* OR "CO hydrogenation"))) OR (AK = ((((syngas OR "synthesis gas" OR "producer gas" OR C1 OR "H2 and CO") NEAR/2 (convers * OR ferment * OR metabol *)) AND ((formate OR acet * OR propion * OR butyr * OR valer * OR capro * OR capryl * OR acid$ OR ethanol OR butanol OR propanol OR pentanol OR hexanol OR octanol OR alcohol$ OR chemical$) NEAR/2 (production OR synthesis))) NOT ("Fischer-tropsch synthesis" OR cataly * OR "CO hydrogenation")))).

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