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Bibliometric Review of State-of-the-art Research on Microbial Oils' Use for Biobased Epoxy

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***Abstract* – Epoxy resins are widely used polymers from which a variety of products are derived and applied in many industries. Most epoxy resins are still obtained from mainly fossil feedstocks, such as epichlorohydrin and bisphenol A, which are also highly toxic. Additionally, fossil derived epoxy resin products are forming non-biodegradable waste at their end of life. Recently the number of studies aiming to find solutions and other raw materials for the replacement of fossil derived epoxy resins has increased, showing that bio-based epoxy resins are a promising alternative. An interesting alternative raw material for bio-based epoxy resins is epoxides derived from microorganisms, such as epoxidized microbial oil. This review article explores and compares the latest solutions for the use of microbial oils in the production of bio-based epoxides, outlines the prospects for their future use and points out the shortcomings of these solutions.**

***Keywords* – Bio-based epoxy; bio-based polymers; bioresource management; environmental impact; single cell oil.**

1. INTRODUCTION

Epoxy products are used in many industries and a variety of applications for materials that require durability in terms of chemical and mechanical characteristics [1], [2] heat-resistance [3], [4], electrical conductivity [5] and sound insulation [6] due to their ability to maintain technical performance over the whole life span. Such materials are used as coatings, paints, composites, adhesives, insulation materials, etc. [7]. The transition towards circular economy [8] has put under spotlight the concerns about use of non-renewable resources as source of epoxy and the recycling of epoxy material at the end of service life [9]. Many studies address the development of environmentally friendly epoxy referred as biobased epoxy or simply bio-epoxy [10]–[13], which has the potential for decreasing environmental footprint and reduction in material waste when appropriate technologies are applied, but this direction has not been explored in-depth yet [14].

The research about novel biobased epoxies is concerning highly topical issues related to material sustainability. At the first glimpse understanding the types of epoxy resins due to the variety of applications and chemicals involved in their production can be consuming. In order to provide insights into the fundamentals and principles for obtaining bio-based epoxy resins this study aims to find the state-of-the-art in biobased epoxy research, focusing on obtainment of epoxy from microbial oils, which have been already recognized as a viable option in the

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production of essential fatty acids [15]. The study consists of two parts including a literature review focusing on scientific articles and a bibliometric analysis of existing literature on biobased epoxy topic, from which conclusions are made regarding the main findings.

2. LITERATURE REVIEW

2.1. Overview of epoxy resins' chemistry

Epoxy resins can be synthesised by source monomers reacting with themselves via cross-linking or via reactions with different hardeners [16]. Epoxy resins are divided into six groups depending on the type of reaction and the compounds used and these groups are: bisphenol-based, novolaks, aliphatic, halogenated, diluents and glycidylamine epoxy resins. Bisphenol-based epoxy resins are the most widely used type of epoxy resins and 95 % of all epoxy materials are bisphenol-based epoxides [17] obtained in the reaction of epichlorohydrin (ECH) with bisphenol A [16].

Bisphenol A is produced via Dianin's general method [18] and the raw materials required for its production are derived from the cumene process [19], which is widely used in the petrochemical industry. The main concerns regarding the widespread use of bisphenol A are related to its estrogen-like activity in the human body [20], which may have long-term health consequences, such as changes in immune function, brain chemistry, enzyme activity, reproductive function [21]–[23], etc.

Epichlorohydrin is produced using both fossil feedstocks (via two step reaction with allyl chloride) and glycerol, a renewable by-product from biodiesel production [24]. Epichlorohydrin is very harmful to human health, it is toxic and carcinogenic and should be used with extreme caution as its vapours are easily absorbed by the body through the lungs and skin [25], [26].

Bisphenol-based epoxy resins are so popular because they have good mechanical and thermal properties, high chemical stability and these materials can be adapted to a wide range of applications [17]. In addition, the production of both bisphenol A and epichlorohydrin requires cheap and widely available raw materials from petrochemical processes [19]. These factors allow bisphenol-based epoxides to dominate existing markets [27], [28]. However, the toxicity of raw materials, their dependence on fossil fuels and their non-biodegradability, which puts a strain on the environment, are the main reasons to search for new alternatives that are biodegradable, use non-toxic renewable raw materials, are economically viable and have properties comparable to bisphenol-based epoxy resins.

Of the other less popular epoxy groups, most use fossil feedstocks in the production and/or the feedstocks are highly toxic and the use of their derived epoxy resins in consumer products should be avoided. One exception is aliphatic epoxy resins obtained by treating unsaturated fatty acids with non-fossil derived acids. These epoxy resins can be produced using renewable raw materials such as vegetable oils, which currently are one of the most widely used bio-based epoxides [17], [29].

2.2. Biopolymer synthesis from plant and microbial oils via epoxide functional groups

Biopolymers is a vast and developing research field. Biopolymers can be obtained from various feedstocks and via multiple different synthesis pathways. One research direction is to use unsaturated fatty acid triglycerides of plant or microbial origin and convert the carbon-carbon double bonds in the fatty acid moieties to epoxide (oxirane) functional groups, with higher chemical reactivity. These functional groups are further involved in

homopolymerization [30] or react with other functional groups in various curing agents to obtain epoxy resins with various properties [13], [31], [32].

Epoxy resins are often used as thermosetting materials, either alone or in various composites. The main bio-sources for such epoxy resins are mentioned found in literature are mentioned in Table 1. There is considerably more scientific literature on plant oils than microbial oils as feedstocks for biopolymers via epoxides. Also, the chemical composition of plant oils is close to microbial oils, therefore we also include plant oils in this review to obtain a wider perspective on the bio-based epoxy research field and its development.

TABLE 1. BIO-SOURCES FOR EPOXY RESINS REPORTED IN LITERATURE

Bio-source	**Curing agent/ Co-polymer**	**Product/ Application**	**Comments**	**Literature source**
Linseed oil	Cyclohexene oxide	Epoxy resins, glass-reinforced composites, and foams	Reaction catalysed by tris(pentafluorophenyl)borane	[33]
Linseed oil	Crystalline citric acid	Thermoset, composite		[34]
Soy oil	Succinic acid, adipic acid, sebacic acid	Thermoset	The epoxy-acids reaction is catalysed by protons	[32]
Soybean oil	Maleopimaric acid	Thermoset	Reaction catalysed by 2-ethyl-4-methylimidazole	[35]
Soybean oil	Fumaropimaric acid	Thermoset	Using N, N-dimethylbenzylamine as the catalyst and sodium bicarbonate as the foaming agent	[36]
Broccoli seed oil	Glutaric, adipic, suberic, sebacic, dodecanedioic, tetradecanedioic, hexadecanedioic acids, o-phenylene diacetic acid	Polymers to be blended with other polymers to improve properties		[37]
Cottonseed and algae oils	Citric acid, tartaric acid	Bioepoxy resins, plant growth substrate	Amberlyst 15-WET (strongly acidic polymeric catalyst) used	[31]
Rhodosporidium toruloides ATCC 10788 microbial oil	Toluene di-isocyanate	Rigid and semi-rigid types of polyurethane foams	Main catalyst: dibutyltin dilaurate, co-catalyst: dimethylethanolamine	[38]
Chlorella vulgaris microalgae oil	Methylene diphenyl diisocyanate	Rigid polyurethane foams	Main catalyst: dibutyltin dilaurate, co-catalyst/cross-linker: triethylenetetramine	[39]
Crude microalgae oil	Diphenylmethane diisocyanate	Polyurethane sheet	Hydroformylation in the presence of a rhodium catalyst $Rh(CO)_2$ and triphenylphosphine ligands was carried out	[40]
Schizochytrium sp. microalgae oil, rapeseed oil	Polymeric 4,4′-methylenebis(phenyl isocyanate)	Urethane-modified isocyanurate foams	N,N-dimethylcyclohexylamine and potassium octoate used as catalysts	[41]

In plant oils, the triglyceride carbon-carbon double bonds are usually converted to epoxide groups via oxidation with hydrogen peroxide and/or peroxy acids, such as peroxy acetic acid or peroxyformic acid. Often hydrogen peroxide and acetic acid is used in combination to produce peroxy acetic acid *in situ* [38]. The possible side reactions are formation of -COOOH, -COOH, and -OOH groups at the carbon atom of the original oxirane group with -OH groups at the adjacent carbon atom [30]. For example, Pawar *et al*. [31] obtain epoxidised cottonseed and microalgae oils through oxidation with hydrogen peroxide and acetic acid. In contrast, Todorovic *et al.* [34] use commercially available, already epoxidized linseed oil as the source for copolymerization.

Solid epoxy resins from epoxidized plant oils have been produced by photo initiated cationic curing, i.e., homopolymerization [30]. These reactions are fast and occur in low temperatures [42]. However, polymers with the desired properties cannot always be obtained. Various curing agents are used to copolymerize epoxidized plant oils. Occasionally, amines are used, but amines are not very reactive towards internal oxiranes, as in epoxidized oils, as well as they readily attack ester bonds in triglycerides, reducing the quality of the products [42]. In the polymerization or the curing reaction, epoxy groups of the epoxidized plant oils open due to the active hydrogen of the curing agents, creating a cross-linked polymer network structure [30]. Cyclohexene oxide has been used as the curing agent to obtain epoxy resins, as well as glass-reinforced composites and foams from epoxidized linseed oil. Tris(pentafluorophenyl)borane is used as the catalyst in these copolymerization reactions. These reactions occur at room temperature and are relatively fast, although post-curing is needed [33].

The commercial curing agents, such as acid anhydrides, amines, amides, and phenols are petroleum-based [34]. Thus, the epoxy resins obtained with these curing agents cannot be considered 100 % bio-based, and sustainable curing agents are sought. Therefore, plant-derived aliphatic organic acids with at least two carboxyl groups are used as curing agents to enable crosslinking in copolymerization of epoxidized plant oils in several studies [31], [32], [34]–[37]. Crystalline citric acid has been used to copolymerize epoxidized linseed oil. The major drawback is that citric acid is insoluble in oil and dispersion of crystalline citric acid in epoxidized linseed oil must be prepared for the reaction to occur. A composite with flax fibres is obtained as the result [34].

The co-polymerization reactions have also been performed in emulsions of the organic acids in double-deionized water and epoxidized soybean oil. The curing agents tested are dicarboxylic acids: succinic acid, adipic acid, and sebacic acid. Protons catalyze the epoxy-acids reactions. The properties of the obtained polymer materials are affected by the chain length of the dicarboxylic acids, and the obtained materials may be used for water-protecting coatings [32].

Epoxidized soybean oil has been also cured with maleopimaric acid, a cycloaliphatic carboxyl acid with an anhydride moiety obtained from rosin. The reaction is catalysed by 2-ethyl-4-methylimidazole and a thermoset is obtained with potential applications as adhesives, composites, and coating [35]. Huang *et al*. [36] use fumaropimaric acid for curing of epoxidized soybean oil, the reaction is catalyzed by 2-ethyl-4-methylimidazole. The obtained product is thermosetting epoxy foams.

Epoxidized broccoli seed oil has been cured with glutaric, adipic, suberic, sebacic, dodecanedioic, tetradecanedioic, hexadecanedioic, and o-phenylene diacetic acids to obtain epoxy resins to be blended with other polymers [37]. Cottonseed and *Chlorella vulgaris* microalgae oils have been epoxidized and cured with citric/tartaric acid to produce bio-based epoxy resins [31]. Algae oil derived from *Chlorella vulgaris* microalgae has been epoxidized with hydrogen peroxide and acetic acid. Polyols are obtained in epoxy-ring opening with

lactic acid or ethylene glycol. Polyols are further cured with methylene diphenyl diisocyanate to yield polyurethane rigid foams [39]. Diisocyanates are used for curing to obtain polyurethanes from microalgae oils also in other studies, for example, methylene diphenyl diisocyanate and diphenylmethane diisocyanate [40].

The methods to extract lipids from microalgae biomass are liquid-liquid extraction, oil press, supercritical fluid extraction (SFE), and ultrasound-assisted extraction [43]. Single cell oils (SCO) have also been used to obtain polymer materials. Uprety *et al.* [38] report conversion of microbial lipids to polyurethane foam. The first two steps are epoxidation of oils and transformation of epoxidized oils to polyols via oxirane ring opening. Epoxidation is carried out with peroxyacid – performic acid is generated *in situ* via reaction between formic acid and hydrogen peroxide. Polyols from epoxidized oil are obtained by reaction with phosphoric acid. Rigid and semi-rigid types of polyurethanes are further produced as polyols react with toluene di-isocyanate.

2.3. Biobased epoxy resins in perspective of sustainable development

Researchers argue that development of epoxy resin from renewable biomass resources instead of petroleum resources can be in line with the sustainable development strategy and in some cases have even higher storage modulus, flexural modulus, and lower water absorption in comparison with conventional applications [44]. Sustainable bio-based epoxy resins from algae biomass were studied by Hidalgo *et al.*, [45] and concluded that *Chlorella vulgaris* can be used for a more sustainable bio-based epoxy resins. Other research has also reported a successful obtainment of a more sustainable bio-based epoxy resin and a realistic opportunity producing fully biorenewable resins at an industrial scale [46], [47]. However, the environmental benefits of the bio-based epoxy resins are still not fully studied yet and have remained unclear due to inconsistency among environmental impacts of polymer production presented in research and not sufficient number of works performed on recycling of the bio-polymer products to provide robust results [48].

Among many scientific evaluations of environmental impact the analytical tool known as Life Cycle Assessment (LCA) is recognized as the best framework for assessing the potential environmental impact of products, processes and systems across an entire supply chain, considering several environmental criteria and allowing to evaluate burden shifting from one stage of lifecycle to another and/or from one environmental impact category to another [49]. LCA can provide environmental benefit evaluation of substituting petroleum-based epoxy resin with bio-based epoxy resin, specifically covering impacts such as resource depletion and waste processing, which are reported as the main benefits of transition towards bio-based epoxy resin applications. Furthermore, the use and design of bio-based polymer products can also be improved with help of LCA guidance [48].

Arias *et al.* [50] performed an LCA in cradle-to-gate perspective of bio-adhesives soy, Kraft lignin, Organosolv, tannin, which can be used as alternatives to the most conventional fossil resins in the production of wood panels and also concluded that there is a wide spectrum of possibilities for producing more environmentally friendly adhesives than conventional fossil resins, and even for paving the pathways towards formaldehyde-free adhesive alternatives. Nonetheless, lignin-based adhesives showed higher environmental impacts than fossil-ones, while soy and tannin-based bio-adhesive showed better environmental performance than fossil resins.

Bechstrom *et al.* [51] performed a techno-economic assessment and LCA of bioplastic production from microalgae with fuel as co-product. Similarly to results of other studies on bioplastics, the study found that there is a clear path to improve the sustainability of the global plastic market using biobased products also including biodegradable resins. Replacement of

petroleum derived resins with algae-based feedstock could reach decrease of GHG emissions between 67 % and 116 %. A more in-depth review on LCA studies of environmental sustainability of polymer nanocomposites based on bioplastics [52] found that GHG emissions and energy consumption is much higher for synthesis of petroleum derived nanoparticles. Even a small amount of petroleum-based nanocomposites can compromise the sustainability of biobased nanoparticles in biopolymers. Thus, the key aspect would be to assess environmental burdens of specific cases occurring in life cycle of biobased polymer.

Summarizing, improvements in environmental performance of bio-based epoxy resins would have a highly positive impact not only on plastics market, but also to energy market by decreasing the dependency on fossil sources, thus, potentially contributing to other indirect environmental benefits by shifting from fossil fuels to biobased fuels, where algae applications for energy purposes are showing to be a potential source for variety of application such as biofuels [53], [54], biogas [55]–[57] and biomethane [58], [59]. Bechstrom *et al.* 2020 [51] concluded that there are already economically competitive pathways for production of algae-based biopolymers. Even so, the potential income under the scenarios of biorefinery concept are still to be evaluated [60].

2.4. Microbial oils' use for biobased epoxy resins

One of the most widely used bio-based epoxides are epoxidized vegetable oils [29]. However, unsatisfactory material properties have been reported for a number of these materials [61]–[63]. According to La Scala and Wool, [63] triglycerides with a higher number of unsaturation sites can be used for bio-based epoxides with improved mechanical and thermal properties. Based on this model, Negrell *et al*. [17] proposed algal triglycerides as a promising alternative to vegetable oil based epoxides. However, algal oils are not the only oils with high concentrations of long polyunsaturated fatty acids, such as docosahexaenoic acid (DHA), eicosapentaenoic acid (EPA), eicosatetraenoic acid (ETA), linoleic acid (LA), α-linolenic acid (ALA) etc. These polyunsaturated fatty acids are found in microscopic algae [64], [65], protists [66], [67], yeasts [68], [69], fungi [70], [71] and bacteria [72]. Hundreds of species of microorganisms can be used to produce single cell oils [15], [73]. Single cell oils, also known as microbial oils, are term coined for all lipids that can be produced by microorganisms. These microorganisms can be cultivated using a wide range of agro-industrial by-products, which significantly reduces the total production costs of these oils, the utilization of by-products reduces the negative impact on the environment, single cell oil production is characterized with low water consumption, production rates are much faster than in case of seasonal harvests of plant biomass for vegetable oil production and the production of single cell oils reduce dependence on the use of agricultural lands and reduces the need to use agricultural lands for the production of non-food raw materials [15], [73], [74]. Consequently, single cell oils in many ways are a promising alternative to vegetable oils to produce bio-based epoxy resins.

Some research groups have identified single cell oils as an interesting alternative to bio-based epoxy production. Negrell *et al*., used the protist *Schizochytrium* sp. DHA-rich oil for synthesis of epoxy materials and foams with various properties [17]. Roesle *et al*. used EPA-rich oil from microalga *Phaeodactylum tricornutum* to obtain an epoxy material with high melting and crystallization temperature [75]. Petrovic *et al*. used microalgae oil to obtain polyol and polyurethane foams [40]. Pawar *et al.* used *Chlorella* sp. microalga oil to obtain rigid polyurethane foam [39]. Later, Pawar *et al*. reported on obtaining an epoxidized cottonseed and microalga *Chlorella* sp. oil material with competitive thermal stability properties [31]. Arbenz *et al.* used *Schizochytrium* sp. oil to obtain epoxide and polyol foams [41]. Hidalgo *et al*. used microalga *Nannochloropsis gaditana* oil to obtain epoxidized

microalgae lipids, although bisphenol A was used to obtain improved mechanical properties of the material [76].

Most of the existing research on this topic uses algae, protist or microalgae oils as the main raw material, which outside the synthesis of epoxy materials are mainly used as feedstock in animal and aquaculture fish feeds and in human nutrition [74]. Single cell oils meant for feed and food use are relatively expensive, although single cell oils can be produced using low-cost by-products and waste products and for the purpose of epoxy material production, these oils do not have to meet the safety requirements usually required for feed and food ingredients [74].

Only a few studies are available on the synthesis of bio-based epoxy resins using oils from other microorganisms. Uprety *et al.* used yeast *Rhodosporidium toruloides* oil to obtain polyol and polyurethane foams. The yeast was cultivated using crude glycerol from biodiesel production as a main feedstock for single cell oil production [38]. Yang *et al.* reported on synthesis of epoxidized microorganism oil using yeast *Trichosporon coremiiforme* oil. The yeast was cultured on a corncob hydrolyzate medium [77]. To the best of our knowledge, these are the only reports on the use of yeast oils in the synthesis of bio-based epoxides, and the use of fungal and bacterial oils in the synthesis of epoxides does not appear to be studied.

The advantages of yeasts, fungi and bacteria are the ability to produce single cell oils using very cheap by-products and waste, their growth rates, oil concentrations in cell biomass and cell densities in the mediums are higher than in algae, protists and microalgae [15], [73]. Therefore, in the future, it would be very interesting to conduct more research using single-cell oils of yeast, fungal and bacterial origin in the production of bio-based epoxides. Although work on the development of new bio-based epoxides using single-cell oils of various origins continues, our bibliometric analysis suggests that bio-based epoxides from single-cell oils are an emerging topic and have been relatively unexplored. In the future, the development of epoxy resins of this origin will require much greater investment, not only in polymer science but also in microbiology, to adapt oil-rich microorganism strains, find most appropriate feedstocks for microbial growth and to optimize the cultivation process to produce single cell oils applicable for bio-based epoxide synthesis.

3. BIBLIOMTERIC ANALYSIS

The selected approach for bibliometric review of research on microbial oil use for biobased epoxy resins applies performance analysis by documents and journal articles published over a period of time, number of citations and mapping of relationship among publications with help of key words. The bibliometric review is performed on documents published in reliable scientific publication abstract and citation database Scopus, which includes a wide variety of disciplines and provides metrics about publications.

The summary of defined three queries is shown Table 2. The selected settings for all queries include search of defined keywords within title, abstract, and keywords of the documents. The documents published in year 2022 are not included in this research to introduce a fair comparison in the analysis of results among published documents for one year over different periods. The keywords used in queries are enclosed in quotation marks.

Query 1 is aiming to perform search for all published documents on topic of biobased epoxy resins, query 2 to perform search for all published journal articles, and query 3 for all published documents on topic of microbial oil use for biobased epoxy resins. Search tools OR is applied for keywords in queries 1 and 2 aiming to distinguish use of similar keywords in different way among published documents. In this way, the search performed with queries 1 and 2 allows to find all documents on topic of biobased epoxy resins not depending on the

terminological differences. The keywords used in query 3, enclosed by brackets, are different options of keywords that must be co-related with keywords in the second brackets linked by search tool AND, thus allowing to find documents that refer to both microorganism oil and biobased epoxy resins.

TABLE 2. DESCRIPTION OF QUERIES IN FOR BIBLIOMETRIC ANALYSIS

No.	Query settings in Scopus	Keywords in query
1.	Keywords in title, abstract and keywords in all published documents before 2022	"bio epoxy", OR "biobased epoxy", OR "bioepoxy", OR "bioepoxy"
2.	Keywords in title, abstract and keywords in Journal articles before 2022	"bio epoxy", OR "biobased epoxy", OR "bio-epoxy", OR "bioepoxy"
3.	Keywords in title, abstract and keywords in all published documents before 2022	("microbial oil" OR "single cell oil" OR "single-cell oil" OR "algae oil") AND ("bio epoxy", OR "biobased epoxy", OR "bio-epoxy", OR "bioepoxy")

The documents found by the defined queries are extracted and used for analysis by number of articles published by year, country, research field, number of articles cited with charts, diagrams and *VOSviewer* software to visualize the identified links among keywords used in literature.

The results of query 1 show 2480 published documents on topic biobased epoxy from period 1978 to 2021. The findings of query 1 are presented in Fig. 1. Only 6 documents were published in 2004, after which publishing tendency changed. There is an exponential growth in number of published documents since 2004. The number of published documents on topic of biobased epoxies in 2021 reached 423.

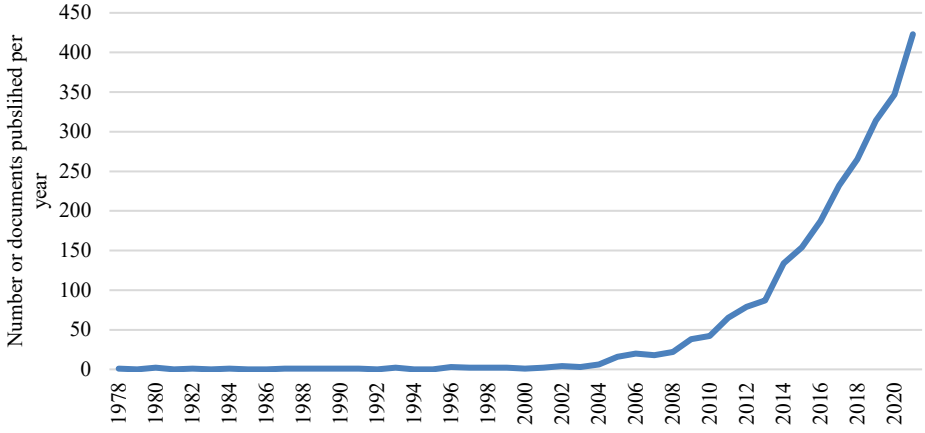


Fig. 1. Number of documents published in Scopus per year on topic of biobased epoxy.

The output of documents per country is shown in Fig. 2. Countries with highest output are China, India, and United States. Among European countries France, Italy, Spain, Germany, and United Kingdom are committing research to the specified topic, together marking a significant output of 25 % of all published documents. Most published authors are Caillol, S. and Boutevin, B. from France with 46 and 30 published documents, and Zhu J. and Liu X. (China) with 35 and 33 published documents shown in Scopus.

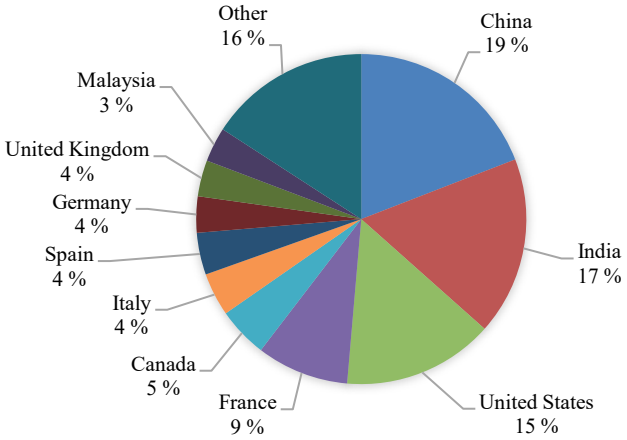


Fig. 2. Published documents in Scopus on topic of biobased epoxy by country.

Journal articles account for 76 % of documents published, followed by conference papers 16 %. The rest of documents found by query 1 are review papers, book chapters and other publication types. Results of query 2 show that among total 1973 published journal articles research fields of Material science, Chemistry and Engineering are most represented (Fig. 3). The journal articles published in the field of Environmental science are accounted only for 6 %, which is considerably low share for a research topic linked with overcoming environmental burdens of fossil-based materials.

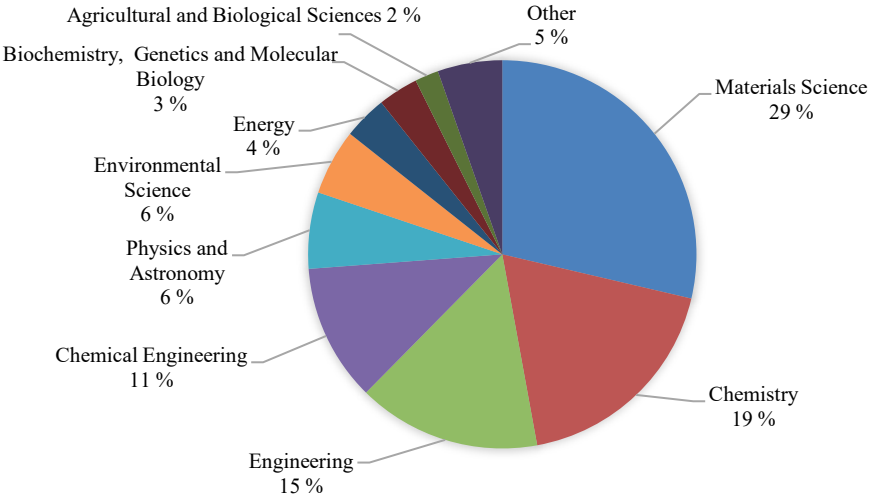


Fig. 3. Journal articles on topic of biobased epoxy by research field.

The number of journal article citations per year is shown in Fig. 4 based on findings of query 2. The tendency of citing similarly to tendency of published documents is increasing exponentially, reaching 44 548 citations in total at the end of 2021. In 2008 approximately 7.7 citations per published article are accounted, while in 2021 the number has increased to 25.9.

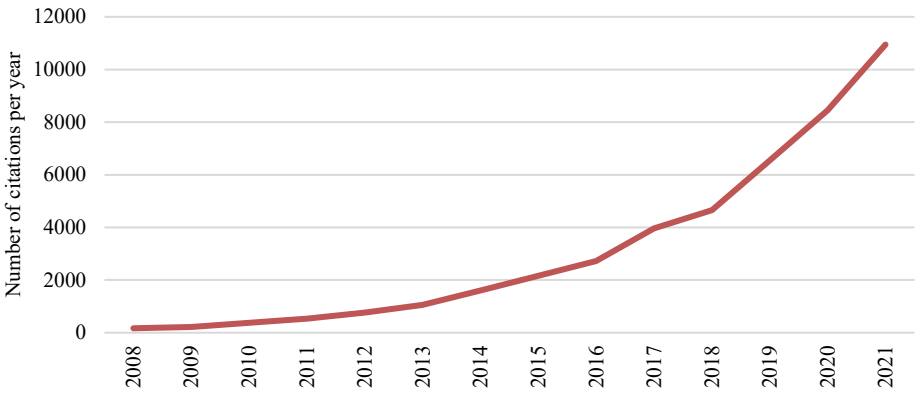


Fig. 4. Number journal article citations on topic of biobased epoxy.

The citing tendency indicates the expansion of the topic among the scientific community. The most popular key co-occurrences of different keywords used in all 1973 published journal articles with a threshold of at least 20 occurrences are shown in Fig. 5. The most often used keywords are mechanical properties, epoxy, epoxy resin. Other keywords often mentioned are composites, thermal properties, thermosets, lignin, bio-based. Consequently, it can be assumed that main research direction on topic of biobased epoxy resins are studies on the mechanical and thermal properties of epoxy resins obtained from resource as lignin and other bio-based resources. Use of words "renewable" and "natural" also appears among the keywords, signifying a well favored reference used in journal articles to environmentally friendly concepts.

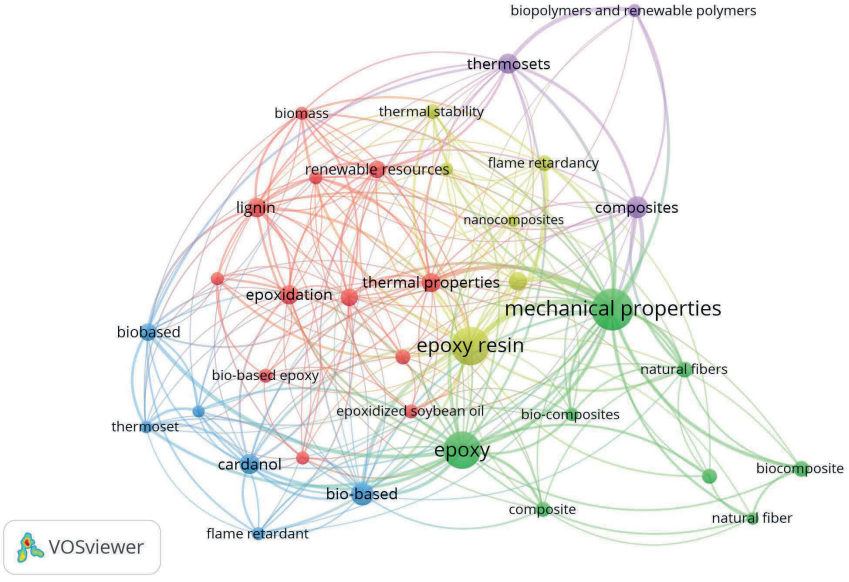


Fig. 5. Keyword co-occurrence in journal articles on topic of biobased epoxy.

The results for search about published articles about microbial oil applications for biobased epoxy made according to query 3 showed only 14 papers published. Among the papers found after screening only 3 journal articles are found to present a study on microbial oil applications for biobased epoxy, which are reviewed in the discussion section.

4. CONCLUSIONS

The review of publications on the topic of biobased epoxy resins showed that there is a rise in the number of published documents in Scopus with the defined keywords for biobased epoxy resins, which also signifies the overall expansion of the biobased epoxy resin research topic, mainly represented in China, India and United States in field of material science, chemistry and engineering. Even more rapid growth is found for the number of citations of journal articles.

Mechanical properties are found to be the biggest co-occurrence keyword in journal articles on topic of biobased epoxy resin. Other specific properties and bioresources used for production of biobased epoxy resin are often reported as co-relation keyword. Regardless, the co-occurrence of keywords renewable resources, biopolymers and renewable polymers among journal articles, the study found there is not enough research on environmental impacts of biobased epoxy resins and this topic should be studied more in depth throughout all the lifecycle of materials, also evaluating the sustainability of such materials.

After conducting the review, study found only a small number of articles presenting and discussing applications on microbial oil use for biobased epoxy resins. Furthermore, there are only couple of reports on the use of yeast oil on the synthesis bio-based epoxides and to the best of authors' knowledge, the use of fungal and bacterial oils in the synthesis of epoxides does not appear to be studied at all. Yeast, fungi and bacteria have significant advantages in regard to their growth rates, oil yields, oil concentrations, cell densities and ability to utilize low-cost substrates, when compared to more widely explored oil producers such as plants, algae, microalgae and protists. Therefore, further research on utilization of yeast, fungal and bacterial oils could significantly contribute to the creation of new competitive bio-based epoxies.

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