# Torrefaction as a Pre-Treatment of Biomass: A Bibliometric Analysis

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## Abstract

*This article sought to investigate biomass torrefaction, analyzing the collaboration network between authors, institutions and countries in order to systematize the dynamics of scientific research on the subject. The systematic evaluation of the articles obtained in the scope of the research was important to provide an overview of the main stakeholders in the academic and institutional scope. This research is characterized as exploratory-descriptive of quantitative nature, whose technical procedure adopted was bibliometric research. A set of 662 documents were extracted from the main collection of Web of Science. The Vosviewer software was used to create scientific collaboration and co-citation networks. It was noted that the number of documents has been growing steadily since 2011, with a high degree of multidisciplinary collaboration and prolific contributions from American and Chinese researchers on this topic. The USA is the country with the largest number of publications (120 publications), followed by China (70 publications). There was a total of 1,894 authors and 594 institutions researching on biomass torrefaction, with SINTEF Energy Research – Norway having the largest number of publications, followed by National Cheng Kung University – Taiwan and Norwegian University of Science and Technology – Norway. The use of bibliometrics proposed here offers a systematic and dynamic approach to scientific research on biomass torrefaction. The identified groupings and collaboration networks presented a specific outline of the contents already published, authors, countries and institutions, in order to contribute as a starting point to future work in the field of biomass torrefaction.*

**Keywords**: bioenergy; thermoconversion; sustainability; research performance; academic networks.

## 1. Introduction

The global scenario of reducing the use of fossil energy and replacing it with renewable and more sustainable sources of energy has been the subject of studies and research in different areas around the world (DALLEMAND et al., 2015, WBA, 2019). And in this context, biomass is presented as an alternative capable of providing positive responses in energy generation and reduction of greenhouse gas emissions, by correcting some disadvantages of its direct application (NUNES and MATIAS, 2020).

The scope of sustainability in the production and commercialization of biomass on a large scale has been increasing strongly as part of a globalized world through *commodities* such as bioenergetics, for example, wood pellets, biodiesel and ethanol. With the participation of academia, research institutions and governments, the industry has been developing and commercializing significantly new technologies and fuels from biomass (IEA, 2019). Solid biomass from forest residues and products, for example, is being increasingly used as a source of commercial energy (DALLEMAND et al., 2015, WBA, 2019).

For industrial application of biomass as a solid fuel for burning or co-burning in the generation of heat and/or energy, it is necessary that characteristics intrinsic to biomass, such as high moisture content, low calorific value, hygroscopic nature and low density, are required improved (BERGMAN and KIEL, 2005, PROSKURINA et al., 2017).

For this, different biomass pretreatment technologies have been presented in the literature, such as drying, densification and torrefaction. The torrefaction technology, to be addressed in this work, consists of the slow heating of the biomass, temperature range between 200 and 300 °C, in an inert environment, aiming at the modification of the physical and chemical composition of the biomass. The solid fuel obtained from torrefaction, called torrefied biomass, has an improved calorific value, hydrophobic, rot-resistant, and with prolonged storage time, when compared to crude biomass (ÁLVAREZ et al., 2018, CHEN et al., 2015, KANWAL et al., 2019).

Based on these characteristics and improvements in torrefied biomass, the commercial interest in using it as solid fuel has increased and are related to gasification, co-burning of biomass-coal, combined heat and power generation, autonomous combustion, fuel production and bio-based chemicals, heating blast furnaces, among other industrial applications (ARTEAGA-PÉREZ et al., 2017, LAU et al., 2018, PAHLA et al., 2018, YANG et al., 2019).

The torrefaction of the biomass can also be combined with densification processes (pelletizing or briquetting), improving the energy content of the biomass per unit mass (BATIDZIRAI et al., 2014, CHEN et al., 2015, SVANBERG and HALLDÓRSSON, 2013). Such improvements favor logistics and generate a positive economic impact at various points in the supply chain (CHEN et al., 2015, SVANBERG and HALLDÓRSSON, 2013).

Studies in the area of torrefaction have increased in recent years and a large number of literature reviews on biomass torrefaction have been published. Some of these reviews have a general scope across the field (BACH and SKREIBERG, 2016, RIBEIRO et al., 2018, SUKIRAN et al., 2017), while others focus on the supply chain (BATIDZIRAI et al., 2014, CIOLKOSZ and WALLACE, 2011, SVANBERG and HALLDÓRSSON, 2013), greenhouse gas emissions and life cycle assessment (MCNAMEE et al., 2016, UBANDO et al., 2019), torrefaction for co-burning biomass and/or new technological advances (ARTEAGA-PÉREZ et al., 2017, BERGMAN et al., 2005). Some studies deal with torrefaction modeling and kinetics (BATES and GHONIEM, 2013, PARK et al., 2015), torrefaction processes and products from different biomasses (ACHARYA and DUTTA, 2016, SUKIRAN et al., 2017), and the development of different types of protocols and scale of reactors used in torrefaction (BASU, 2018, BATIDZIRAI et al., 2013).

Each study presents information about a certain area of the research field, but there is a gap in additional analyzes using bibliometric tools, which can assist in *insights* that have not been fully addressed.

Thus, this work aimed to present the mapping of publications in the field of biomass torrefaction from bibliometric analysis, aiming to highlight the main collaboration networks between authors, institutions, and countries. To the best of our knowledge, no one has yet investigated the bibliometric analysis of biomass torrefaction as in the present study.

## 2. Conceptualization on Torrefaction

The torrefaction consists of the thermal treatment of biomass at temperatures between 200 and 300 °C, in an inert atmosphere, aiming at changing the chemical composition and energy value of the generated solid product. It is an endothermic process, which leads to the improvement of energy density, ignition, grinding, elevation of C/O and C/H ratio, hydrophobicity, homogeneity and reduction of toughness, fibrous structure, moisture and microbial activity of crude biomass (BERGMAN and KIEL, 2005, PRINS et al., 2006b). The basic concept for torrefaction processes is commonly the same, although there are variations in the process for the different reactor concepts (Figure 1).

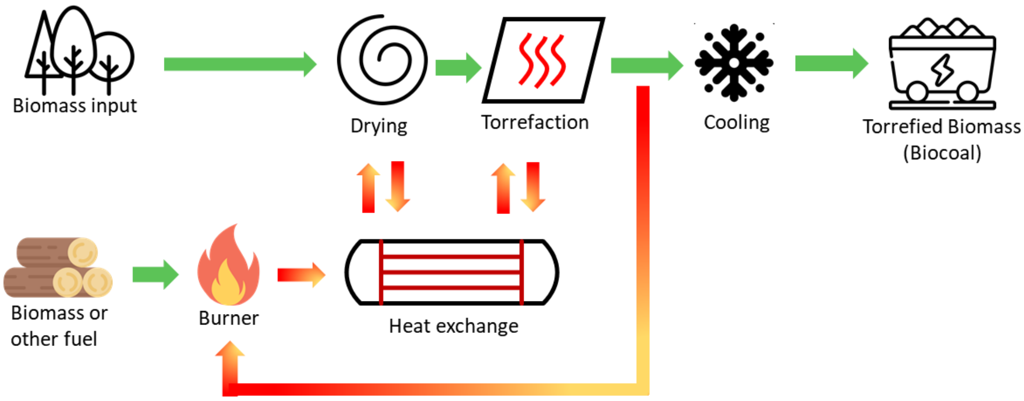


Figure 1: Overview of torrefaction process (adapted from Koppejan et al. (2012)).

Torrefied biomass has a lower moisture content, volatile material and calorific value when compared to its original raw biomass (ACHARYA and DUTTA, 2016, YANG et al., 2019), and the combustibility and burning performance of pretreated biomass is, therefore, higher than crude biomass. When compared to crude biomass, the energy density of torrefied biomass is closer to that of coal (PAHLA et al., 2018, YANG et al., 2019). Torrefied biomass is more suitable for use as a solid fuel, since its use as a raw material is capable of improving the performance of thermochemical processes, such as pyrolysis and gasification (PRINS et al., 2006a) and, in boilers and blast furnaces (BERGMAN et al., 2005, LAU et al., 2018).

The products obtained from conventional torrefaction include gases, liquid and solid, similar to pyrolysis, but solid fuel is the main product of torrefaction. The gaseous product normally contains 10% of the biomass energy and its low calorific value has few practical applications (VAN DER STELT et al., 2011, WANNAPEERA et al., 2011). The main non-condensable products mainly comprise CO, $CO_2$, $H_2$ and fractions of $CH_4$, toluene, benzene and low molecular weight hydrocarbons are also detected (ÁLVAREZ et al., 2018, PRINS et al., 2006b). The liquid product varies from brown to black, depending on the torrefaction temperature, and consists of condensable components such as water, acetic acids, alcohols, aldehydes and ketones (CHEN et al., 2015, CHEW and DOSHI, 2011).

Torrefaction is characterized by different process parameters, which include temperature, reaction time, type of biomass and particle size. Temperature and reaction time are the main parameters in the implementation of this pre-treatment of crude biomass. Based on temperature, conventional biomass torrefaction processes can be classified as light, mild and severe torrefaction, where temperatures are in the range of approximately 200-235, 235-275 and 275-300 °C, respectively (MEDIC et al., 2012, WANNAPEERA et al., 2011).

As for the torrefaction time, the longer the reaction time, the greater the energy density of the solid fuel resulting from the increase in the carbon content in the torrefied biomass (MEDIC et al., 2012, ROUSSET et al., 2011). In this case, the longer reaction time results in the higher energy expenditure of the torrefaction. Thus, the torrefaction temperature parameter has a greater influence on the change in biomass properties than the reaction time (KANWAL et al., 2019).

The size of the biomass particles influences the reaction mechanism, the kinetics and the duration of the process for a specified heating rate (MAMVURA and DANHA, 2020). The type of biomass is another important parameter of influence on torrefaction, considering that hemicellulose is the component that most decomposes in the torrefaction temperature range. It is observed that, for a biomass with a high hemicellulose content, a high loss of mass is expected during the torrefaction process.

In addition to conventional or non-oxidative torrefaction, biomass torrefaction can also be carried out in other environments, such as gases containing oxygen, high pressure water or steam, impregnated with ionic liquids, among other environments. In general, there are different torrefaction processes based on the reaction medium, such as: Dry torrefaction (BASU, 2018, BERGMAN and KIEL, 2005, MEDIC et al., 2012), Wet torrefaction (BACH and SKREIBERG, 2016, HOEKMAN et al., 2011), and torrefaction with Ionic Liquids (CAO et al., 2009, SARVARAMINI et al., 2013, ZHANG et al., 2017). Dry torrefaction is carried out at temperatures varying between 200-300 °C, in an inert environment and ambient pressure (CHEN et al., 2015, CHEW and DOSHI, 2011, CIOLKOSZ and WALLACE, 2011), as previously presented. Wet torrefaction or hydrothermal carbonization (HTC) occurs in a hydrothermal atmosphere in the temperature range between 180-260 °C and higher pressure than water vapor (ARTEAGA-PÉREZ et al., 2017, HOEKMAN et al., 2011). The use of ionic liquids at room temperature (RITLs) in the torrefaction process can be useful due to its chemical and thermal stability, non-flammable and low vapor pressure, being an alternative to conventional volatile organic solvents (CAO et al., 2009, SARVARAMINI et al., 2013).

The reactors generally used in torrefaction are identified according to Dhungana et al. (2012) as: laboratory, pilot or commercial scale. Among the main types of laboratory reactors, there are: (i) fixed bed torrefaction reactor, (ii) microwave torrefaction reactor, (iii) rotary drum reactor and (iv) fluidized torrefaction reactor. Regarding the commercial torrefaction technologies available on the market, characterized by their reactor designs, they can be grouped based on the mixing pattern criteria and based on the heat exchange mechanism (BATIDZIRAI et al., 2013, DHUNGANA et al., 2012). In this context, dry torrefaction is the technology most commonly applied on a commercial scale (RIBEIRO et al., 2018) since most current torrefaction technologies are based on concepts of existing reactors intended for other purposes, such as drying or pyrolysis (KIEL, 2011), requiring only improvements in technical protocols for torrefaction applications.

It is verified that the torrefaction is in constant technological development, at different levels of innovation, both in academia and in the industry, seeking to improve operational performance, standardization and quality of the final product. The diversity of interrelated areas shows a wide field for the development of new research and the application of protocols at other scales.

## 3. Bibliometric Method

This research is characterized as exploratory-descriptive of quantitative being, whose technical procedure adopted was bibliometric research. As defined by Pritchard (1969), bibliometric study can be defined as "the application of mathematical and statistical methods to books and other communication media". Bibliometric analyzes result in indicators of research quantity and performance, and can also provide measurements of the connections between researchers and research areas through the analysis of networks, collaborations and citations(REHN et al., 2014).

The analysis of collaboration networks using bibliometric tools can further enhance the identification of the influence of already established or emerging areas, and can also assist in the identification of research groups, researchers and institutions, showing how the various areas of knowledge may have emerged from the characteristics of the identified authors and institutions (FAHIMNIA et al., 2015).

For the analysis of the information and the generation of results, Figure 2 shows the stages of the bibliometric study of publications related to biomass torrefaction.

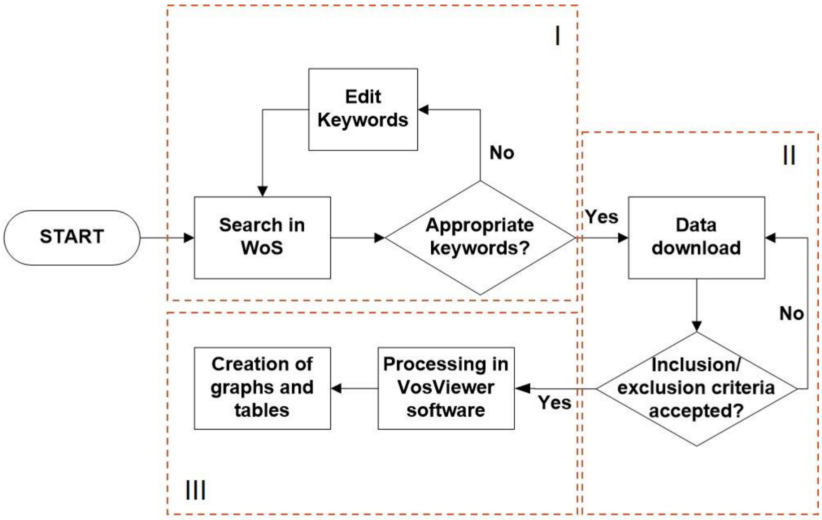


Figure 2: Procedure for bibliometric analysis (adapted from Ochoa et al. (2019)).

In the first step, the search for the subject determined by the keywords that facilitate and cover the largest amount of information to be analyzed is defined. The keywords have been properly assessed during the biomass torrefaction technology aimed at improving the energy raw materials, as the topic torrefaction is several times also used as process grain toast (roasting).

The terms used in the research emphasized the fields of “biomass”, “torrefaction”, and “densification”, based on variations of the terms and combined using Boolean operators, applied to the time interval from 2000 to 2019, with information obtained on 01/11/2020. The expressions and/or keyword terms should appear in the title. The following search expression was used:

**TI = ((torrefaction OR torrefied OR torrefying) AND (biomass OR lignocellulosic OR wood OR "agri-wastes" OR "agricultural wastes" OR "agricultural residues" OR "forest residues" OR "forest waste "OR biocoal OR briquett * OR pellet *))**

The research database was Clarivate Analyticals' Web of Science Core Collection (WoS), for the metric and relevance of studies available from the keywords used. WoS has wide coverage of the main journals available in the world, published in indexed journals and classified according to the impact factor of the Journal Citation Reports (JCR).

In the second step, based on the general procedure for obtaining research reports and data sets from the WoS database, the articles were coded according to: year of publication, place of publication, authorship and co-authorship, keywords, periodicals/journals and publication language.

It was considered that each article should have up to 10 authors or organizations or countries, and at least 05 documents in the database. In addition to the initial data processing using Excel spreadsheets (Microsoft Office), the VOS Viewer software was chosen due to its ability to work with large data sets and to develop a range of analysis options and innovative investigations, creating intuitive images that assist in data analysis (FAHIMNIA et al., 2015).

In the third stage, filters were established using inclusion/exclusion criteria for publications that met the biomass torrefaction field. The following criteria were formulated:

a) Was the publication reported in a peer-reviewed journal article?
b) Did the publication investigate or address the development of torrefaction technology?
c) Did the publication report research methods and provide scientific evidence about biomass torrefaction and biomass energy improvement?
d) Does the publication have the complete record in the database and available bibliographic references?

The development and scientific analysis were based on the co-authorship of the documents published in journals, especially in journals, aiming to identify the main clusters of the research field and focal points of the collaboration networks. Finally, graphs and tables were elaborated for the discussion presented in this article.

Thus, we sought to identify and filter the scope of the database to be analyzed, in order to ensure that the information can be interpreted reliably and that the study is correctly classified, as proposed by Kitchenham (2004). The results of the analysis and data synthesis will be presented in the following subsections, highlighting the main collaboration networks of authors, institutions and countries, as well as profiles of trends in research and development of biomass torrefaction over the applied time interval.

## 4. Bibliometric Analysis of Networks

### *4.1 Characteristics of Publications*

662 publications were obtained that met the objectives defined in this study from the main collection of WoS, published in the period from 2000 to 2019. Among the different types of publications, most were from Articles (73.3 %), Proceeding Paper (17.4 %) and Reviews (3.6 %). The predominant languages of the publications were English (98.2 %), followed by German (0.45 %), Polish (0.45 %) and Korean (0.3 %).

Figure 3 shows the evolution of research in the field of biomass torrefaction over time. The frequency of publications over the analyzed period has been quite regular in the number of publications over the years. As of 2011, there is a presence of linear growth in the number of publications (p-value: $<0.004$) and a strong relationship strength ($R^2$: 0.953), based on the regression test performed.

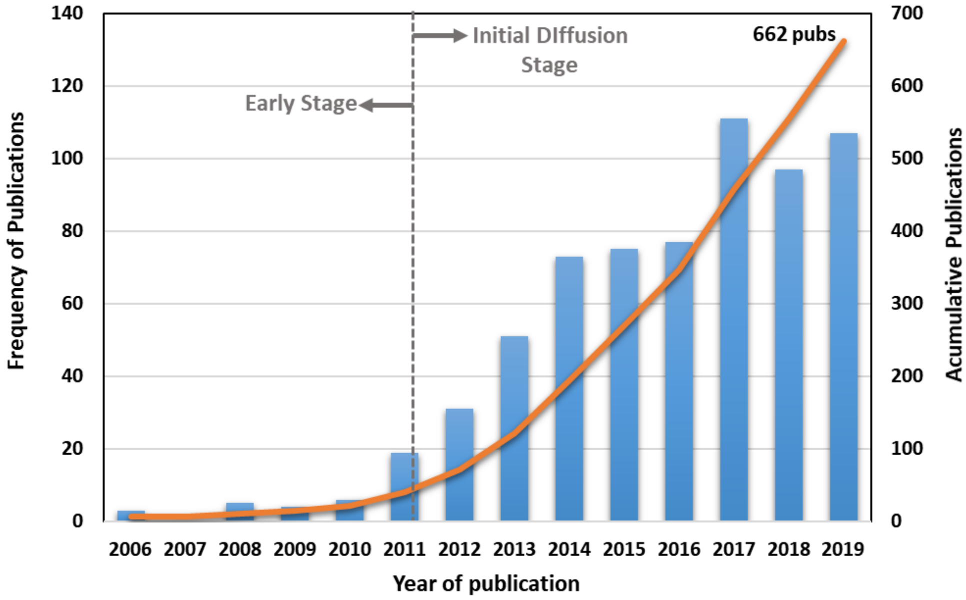


**Figure 3**. The annual number of periodical articles during 2006–2019.

No documents were identified in the WoS 2000, 2001, 2005 and 2007 databases, referring to the search field for the keywords used for biomass torrefaction. Similarly observed by Perea-Moreno et al. (2019), identified that there was no significant growth in the scientific production of biomass as a renewable source, in the period 1978-2006.

From 2006 to 2010, the rate of scientific publications fluctuated at low values (3 to 10 publications). From 2011 onwards, it can be seen that the number of scientific publications increased significantly (up to 61.9%) concerning previous years. In the period from 2012 to 2016, the number of publications was more intensified and progressive, followed by the period of 2017-2019 with even higher values, respectively, 111, 97 and 107 publications per year. Thus, research in this field has been in constant development over the past 10 years and can be characterized by the beginning of the diffusion and maturation of technology. Table 1 shows the main journals that published in the torrefaction field obtained in the WoS database between 2000 and 2019.

**Table 1**. The most productive journals during 2000-2019.

| Journals | Total Volumes[a] | Total Citation[b] | Impact Factor (JCR)[c] | Energy & Fuels Category |
|---|---|---|---|---|
| Energy & Fuels | 56 (1°) | 1451 (7°) | 3,421 (Q2) | 55° |
| Bioresource Technology | 51 (2°) | 2811 (1°) | 7,539 (Q1) | 13° |
| Fuel | 49 (3°) | 1710 (6°) | 5,578 (Q1) | 24° |
| Energy | 37 (4°) | 2565 (2°) | 6,082 (Q1) | 20° |
| Biomass & Bioenergy | 35 (5°) | 1813 (5°) | 3,551 (Q2) | 53° |
| Applied Energy | 31 (6°) | 1853 (4°) | 8,848 (Q1) | 9° |
| Journal of Analytical and Applied Pyrolysis | 23 (7°) | 1916 (3°) | 3,905 (Q2) | 41° |

| | | | | |
|---|---|---|---|---|
| Fuel Processing Technology | 16 ( 8°) | 887 (9°) | 4,982 (Q2) | 29° |
| Bioresources | 16 (9°) | 116 (15°) | 1,409 (Q1) | - |
| Energies | 11 (10°) | 119 (14°) | 2,702 (Q3) | 63° |
| Energy Conversion and Management | 11 (11°) | 485 (10°) | 8,208 (Q1) | 11° |

[a]Total Volumes: Total number of volumes and the ranking of the total of number of volumes; [b]Total Citation: Total number of citations and the ranking of the total of number of citations; [c]2019 Journal Impact Factor and quartile in the category Energy & Fuels; [d]Title discontinued as of 2019.

About 51 % of the articles related to biomass torrefaction, in the period 2000-2019, were published in the main journals listed. These results show a trend of publication in specialized high impact journals that range from the chemical conversion of raw materials, design and operation of plants and equipment, as well as the development, production, use, application, conversion and management of non-renewable fuels (such as wood, coal, oil and gas) and renewable energy sources (solar, wind, biomass, geothermal, hydroelectric). It is important to note that journals that publish more articles are more likely to be cited, which may cause a tendency to increase the number of citations. Gargouri et al. (2010) defend in this respect empirical results in favor of the positive causal relationship between open access and the number of citations.

This information aims to assist in the prospecting of the database and in the development of high impact research in the field of biomass torrefaction, in addition to contributing to the choice of the journals to be published.

Table 2 presents the 10 most cited articles in the period from 2000 to 2019 related to biomass torrefaction, this shows that the content present in these documents has been essential for the development of different research areas.

**Table 2**. The 10 most citations articles during 2000-2019.

| **Articles** | **Reference** | **Total Citation** | **Year** |
|---|---|---|---|
| Biomass upgrading by torrefaction for the production of biofuels: A review | Van der Stelt, M.J.C.; Gerhauser, H.; Kiel, J.H.A.; Ptasinski, K.J. | 719 (1°) | 2011 |
| Impact of torrefaction on the grindability and fuel characteristics of forest biomass | Phanphanich, M.; Mani, S. | 477 (2°) | 2011 |
| Influence of torrefaction on the grindability and reactivity of woody biomass | Arias, B.; Pevida, C.; Fermoso, J.; Plaza, M.G.; Rubiera, F.; Pis, J.J. | 470 (3°) | 2008 |
| A state-of-the-art review of biomass torrefaction, densification and applications | Chen, W.H.; Peng, J.H.; Bi, X.T.T. | 446 (4°) | 2015 |
| More efficient biomass gasification via torrefaction | Prins, M.J.; Ptasinski, K.J.; Janssen, F.J.J.G. | 393 (5°) | 2006 |
| Torrefaction of wood - Part 2. Analysis of products | Prins, M.J.; Ptasinski, K.J.; Janssen, F.J.J.G. | 373 (6°) | 2006 |

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|---|---|---|---|
| Torrefaction of wood - Part 1. Weight loss kinetics | Prins, M.J.; Ptasinski, K.J.; Janssen, F.J.J.G. | 360 (7°) | 2006 |
| Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. Techno-economic evaluation of torrefaction, fast pyrolysis and pelletization | Uslu, A.; Faaij, A.P.C.; Bergman, P.C.A. | 355 (8°) | 2008 |
| A study on torrefaction of various biomass materials and its impact on lignocellulosic structure simulated by a thermogravimetry | Chen, W.H.; Kuo, P.C. | 309 (9°) | 2010 |
| Recent advances in biomass pretreatment - Torrefaction fundamentals and technology | Chew, J.J.; Doshi, V. | 301 (10°) | 2011 |

The most cited article (719 citations) on the WoS platform in this field was the "*Biomass upgrading by torrefaction for the production of biofuels: A review*", published in 2011 in the journal Biomass & Bioenergy, by Van der Stelt et al. (2011). In this review article the general characteristics of the torrefaction are presented, a brief history of the torrefaction, the overview of different mass and energy balances, the applications and the economic potential of the torrefaction.

As we can see, the top 10 most cited articles in the field of biomass torrefaction were published between 2006 and 2011, except for the article "*A state-of-the-art review of biomass torrefaction, densification and applications*" dated 2015. It is commonly agreed in the literature that pre-treatment by torrefaction improves different characteristics of the fuel, making it more suitable for both domestic and industrial applications. Although these documents support the scientific basis in the field of torrefaction, it is important to state that they do not guide current and future trends. This subject will be better addressed in the following sections of this work.

### *4.2 Countries and Institutions Contributions Analysis*

Publications can be presented according to the contribution of different countries, territories and institutions through the analysis of postal addresses of publications. The ranking of the top 10 countries regarding the number of scientific publications in the field of biomass torrefaction is shown in Table 3.

**Table 3**. International collaboration of top countries.

| Country | TP | TPR | TC | TCR | TS | TSR |
|---|---|---|---|---|---|---|
| USA | 120 | 1 (14.5) | 3865 | 1 (15.8) | 53 | 1 (11.7) |
| China | 70 | 2 (8.5) | 2395 | 4 (9.8) | 45 | 2 (9.9) |
| Canada | 53 | 3 (6.4) | 1921 | 5 (7.9) | 36 | 3 (7.9) |
| France | 44 | 4 (5.3) | 1496 | 6 (6.1) | 28 | 5 (6.2) |
| Norway | 37 | 5 (4.5) | 948 | 7 (3.9) | 29 | 4 (6.4) |
| Taiwan | 36 | 6 (4.3) | 2587 | 3 (10.6) | 24 | 6 (5.3) |
| South Korea | 35 | 7 (4.2) | 473 | 17 (1.9) | 16 | 10 (3.5) |
| Netherlands | 34 | 8 (4.1) | 2722 | 2 (11.1) | 15 | 12 (3.3) |

| | | | | | | |
|---|---|---|---|---|---|---|
| Brazil | 30 | 9 (3.6) | 562 | 13 (2.3) | 16 | 11 ( 3.5) |
| Malaysia | 29 | 10 (3.5) | 627 | 11 (2.6) | 11 | 14 (2.4) |

TP: Total number of articles; TPR (%): The ranking and percentage of the total number of articles; TC: Total number of citations; TCR (%): The ranking and percentage of the total number of citations; TS: Total link strength; TSR (%): The ranking and percentage of the total link strength.

The USA is the country with the largest number of publications (120), followed by China (70), Canada (53), France (44), Norway (37), Taiwan (36), South Korea (35), Germany (34), Brazil (30) and Malaysia (29). Considering the countries with at least 5 publications on the topic, there is a strong concentration of scientific production, so that only 10 countries produce around 59 % of the total publications. It is important to report that although Taiwan and Germany are respectively in 6th and 7th place in the ranking of publications, they are highly cited passing the placing of 3rd and 2nd place in countries most cited in the field of torrefaction.

In this context, a temporal analysis of the behavior of scientific production in the countries with the largest number of publications in the field of biomass torrefaction is opportune. Figure 3 shows the evolution of the number of publications in the 6 countries with the highest scientific production.

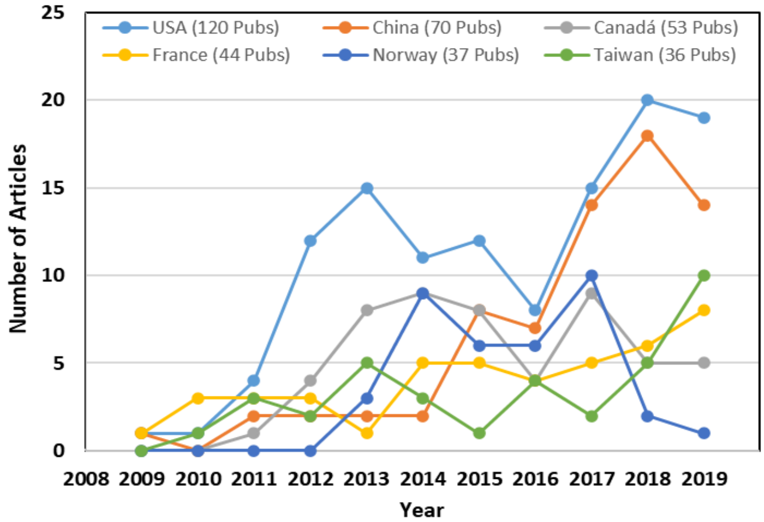


**Figure 3**. Annual growth curve of the top six countries.

It is possible to observe the significant increase in scientific production in the USA, followed by China over the last 10 years in the field of torrefaction. In general, the main countries showed greater stability in the growth of publications from the year 2015, except for Norway for the years 2018 and 2019.

This fact is taken into account due to the set of goals and actions observed worldwide aiming to mitigate climate change in the last 5 years, thus causing an intense search for energy alternatives to the use of fossil fuels. In a way, biomass has a strong potential in contributing to the reduction of greenhouse gas emissions. And torrefaction technology as an alternative capable of transforming biomass residues into solid fuels (NUNES and MATIAS, 2020) and directly replacing coal in generating electricity, especially those from energy forests. It turns out that the growth in the number of publications with different co-authors and areas of concentration has drawn attention in the development of torrefaction.

According to Giuliani (2005), identifying how knowledge transfer flows in collaboration networks or clusters is crucial for understanding how innovation happens. Figure 4 presents seven well-defined clusters of the collaboration network between countries, elaborated in the VOSviewer software from the WoS database, using the list of at least 5 documents published by country.

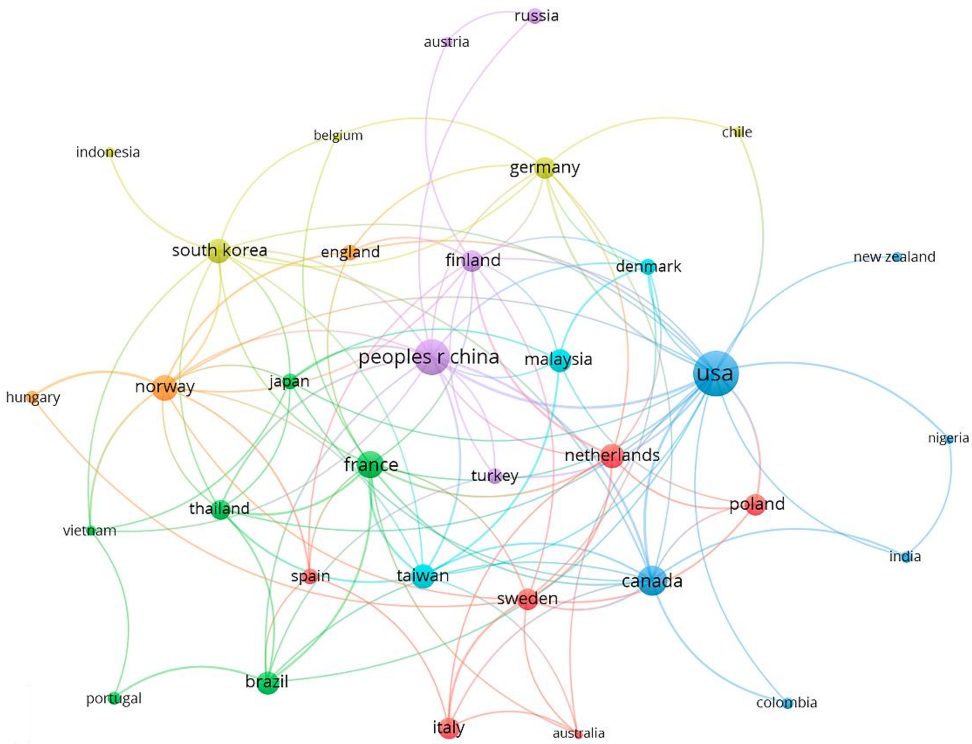


**Figure 4**. The cooperation network of the countries.

The origin of the publications made in the period from 2000 to 2019 was from 59 countries, however, when considering at least 5 publications per country, a collaboration network of 34 countries in 7 clusters was obtained. The clusters in Figure 4 are identified as:

*i. Blue cluster,* whose countries are the USA, Canada, Colombia, India, New Zealand and Nigeria. It is the cluster with the highest percentage of publications (24.3 %).

*ii. Violet cluster,* mostly Asian countries, including: China, Russia, Turkey, Austria and Finland. It is the second largest cluster in publications (16.2 %) along with the red cluster.

*iii. Red cluster*, representing about 16.2 % of publications, has the leading position in publications in the Netherlands, mainly composed of the following European countries: Australia, Italy, Holland, Poland, Spain and Sweden.

*iv. Green cluster,* with about 15.7 %, is associated with countries from different geographic regions, with greater representation of France in publications, with members in Brazil, Japan, Portugal, Thailand and Vietnam.

*v. Light blue clusters,* composed of the countries: Denmark, Malaysia and Taiwan. This cluster represents about 9.8 % of the publications on biomass torrefaction.

*vi. Yellow cluster,* with about 9.4 % of the total publications, South Korea and Germany lead, followed by Chile, Indonesia and Belgium.

*vii. Orange cluster*, representing the least representative cluster in publications, with about 7.7 % of the publications related to biomass torrefaction, are the countries England, Hungary and Norway.

The USA and China countries present greater intensity in publications and centrality in the cooperation network, being in different clusters (blue and violet, respectively). It appears that the country networks are placed in such a way that the distance between them indicates, approximately, their relationship according to the aggregation criteria used by the VOSViewer software (VAN ECK and WALTMAN, 2010), thus conforming to the map of Figure 4. This construction and analysis of the network of countries has the emphasis on analyzing and visualizing large sets of bibliographic data from the distance-based approach. As noted in Table 2 and Figure 3, countries such as USA and China have a greater volume of publications and intensity in the collaboration network in the field of biomass torrefaction. There is still, despite being in different clusters, a strong research relationship due to the thickness of the connection line as shown in Figure 4.

With the increase in the growing energy demand, different public and private institutions have directed their research on solid fuels to the emphasis on energy improvement, reduction of greenhouse gases and optimization of production processes. Table 4 shows the main institutions that have published the most in the field of biomass torrefaction. About 594 institutions researching torrefaction were verified, making it necessary to use the filter of having published at least 05 co-authorship documents. Thus, 60 institutions were developed that developed publications in the field of torrefaction.

**Table 4**. The performance of the most productive organizations.

| Organization | TP | TPR | TC | TCR | TS | TSR |
|---|---|---|---|---|---|---|
| SINTEF Energy Research, Norway | 30 | 1 (4.5) | 799 | 6 (4.0) | 39 | 1 (10.6) |
| National Cheng Kung University, Taiwan | 28 | 2 (4.2) | 1884 | 1 (9.4) | 28 | 3 (7.6) |
| Norwegian University of Science and Technology, Norway | 26 | 3 (3.9) | 620 | 9 (3.1) | 36 | 2 (9.8) |
| University of British Columbia, Canada | 17 | 4 (2.6) | 1158 | 4 (5.8) | 21 | 5 (5.7) |
| Agricultural Research for Development - Cirad, France | 14 | 5 (2.1) | 679 | 7 (3.4) | 11 | 8 (3.0) |
| Technical University of Denmark, Denmark | 14 | 5 (2.1) | 523 | 13 (2.6) | 9 | 11 (2.4) |
| Umea University, Sweden | 13 | 7 (2.0) | 460 | 14 (2.3) | 11 | 9 (3.0) |
| Zhejiang University, China | 11 | 8 (1.7) | 676 | 8 (3.4) | 6 | 19 (1.6) |

| | | | | | | |
|---|---|---|---|---|---|---|
| Åbo Akademi University, Finland | 10 | 9 (1.5) | 276 | 24 (4.3) | 6 | 20 (1.6) |
| Energy Research Centre of the Netherlands – ECN, Netherlands | 10 | 9 (1.5) | 868 | 5 (1.4) | 4 | 27 (1.1) |
| Hungarian Academy of Sciences, Hungary | 10 | 9 (1.5) | 173 | 33 (1.1) | 23 | 4 (6.3) |
| Swedish University of Agricultural Sciences, Swedish | 10 | 9 (1.5) | 229 | 27 (0.9) | 9 | 12 (2.4) |
| Federal University of Viçosa, Brazil | 10 | 9 (1.5) | 71 | 49 (0.4) | 0 | 46 (0.0) |

TPR(%): The ranking and percentage of the total number of articles; TCR(%): The ranking and percentage of the total number of citations; TSR(%): The ranking and percentage of the total link strength.

SINTEF Energy Research - Norway leads with the largest number of publications (30 publications), followed by National Cheng Kung University - Taiwan (28 publications) and Norwegian University of Science and Technology - Norway (26 publications). The position of National Cheng Kung University and the University of British Columbia stands out for the high number of citations to their work. This may be related to the quality and innovation of your publications. Similarly, Eindhoven University of Technology - Netherlands (5 publications) and National University of Tainan - Taiwan (8 publications) draw attention to the number of citations concerning the number of publications, 1845 and 1321, respectively. It is important to note that SINTEF is one of the largest independent research organizations in Europe, having as a strong characteristic of the multidisciplinary and collaboration between various research groups throughout the organization.

In order to make a temporal cut of the four main institutions, Figure 5 shows the annual variation in the number of publications in the period from 2012 to 2019.

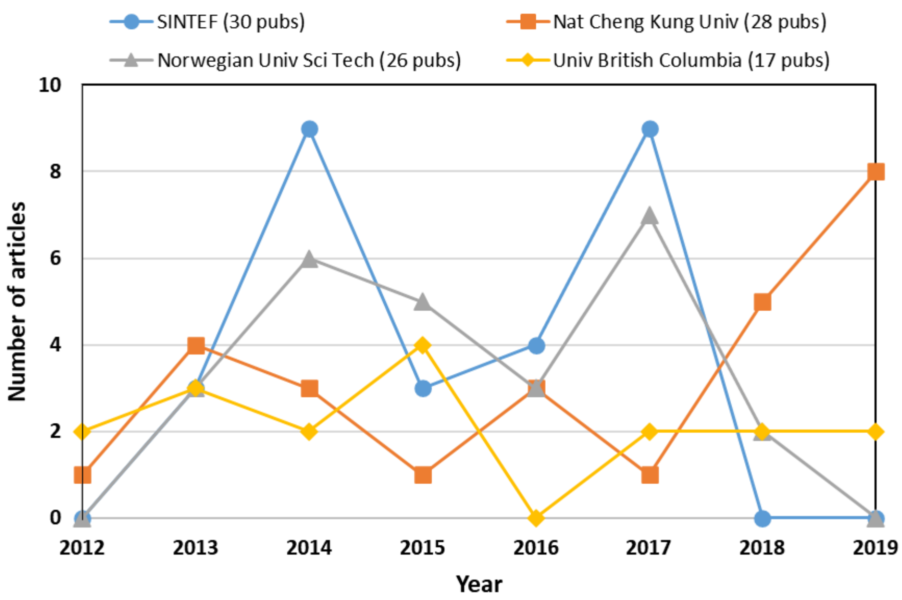


**Figure 5**. Annual growth curve of the main institutions.

Although the United States and China have the largest volume of publications, American and Chinese institutions did not appear individually at the top of the list. Caused by the difference in metrics between the authors and institutions where they develop the research. The four institutions that published the most varied considerably in the annual number of publications over the analyzed period. Among the institutions analyzed, National Cheng Kung University has presented an increasing number of publications in recent years (2017-2019). In contrast, SINTEF showed discontinuity in publications in 2018 and 2019 in the biomass torrefaction field, corroborating the fall in publications from Norway.

Figure 6 shows the general cooperation network of the institutions that have published in the field of biomass torrefaction, as also seen in Table 2. While Figure 7, the organizations with the greatest strength of the co-authorship link were selected to compose the network interinstitutional interconnection.

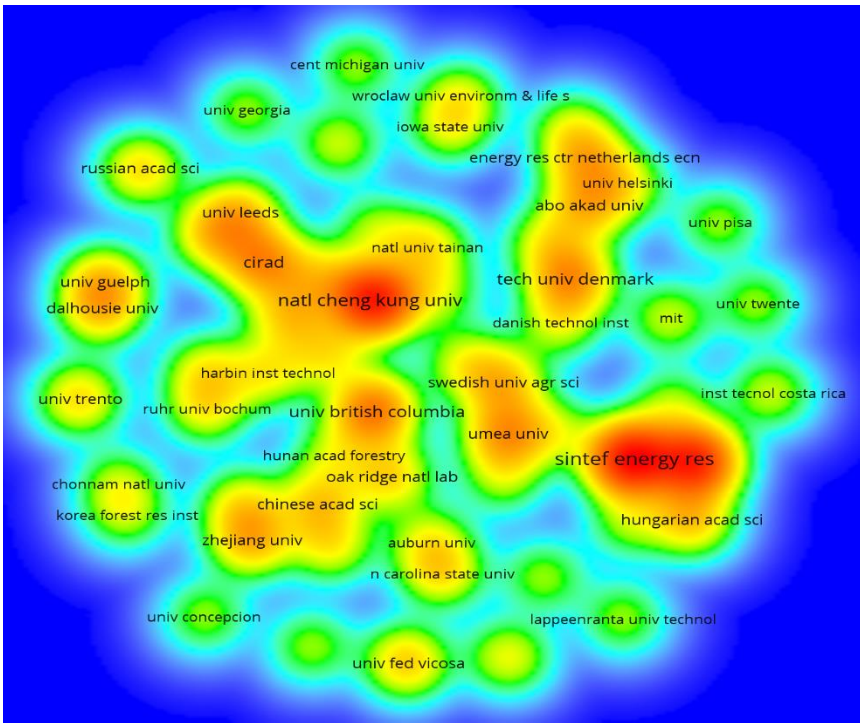


**Figure 6**. Density visualization of the institution's cooperation network.

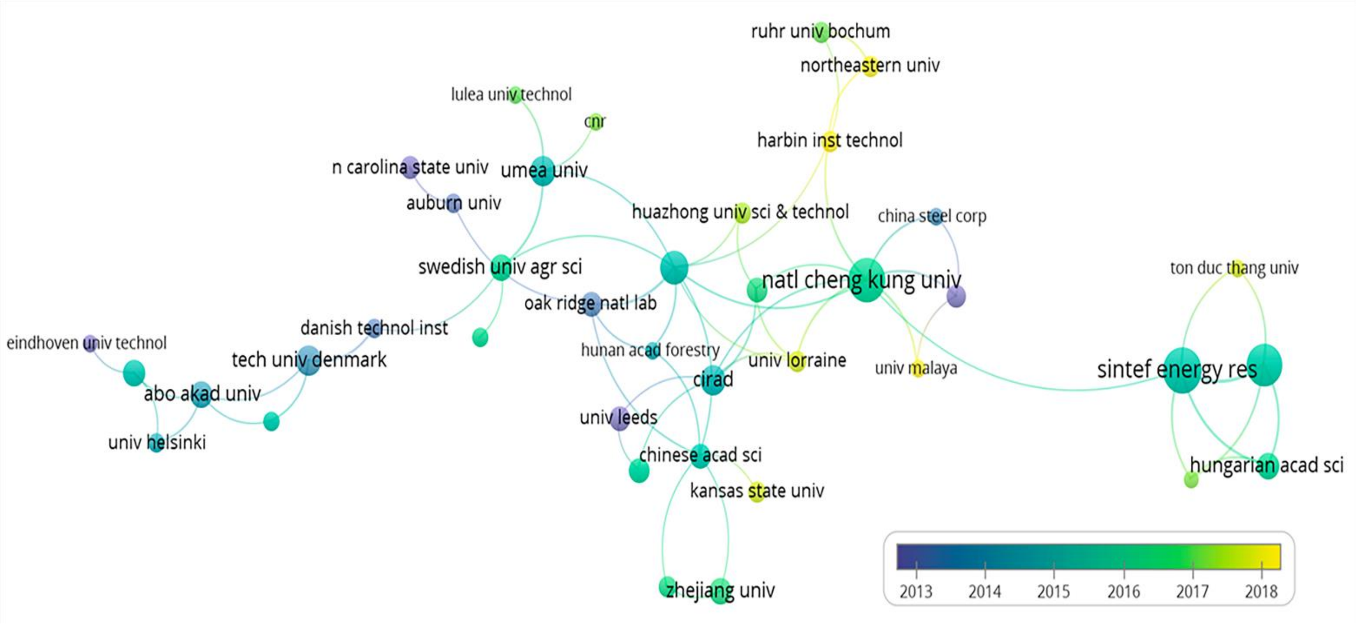


**Figure 7**. The cooperation network of interconnected institution.

The connection between the different institutions is related to different forms of scientific cooperation between them, be it projects, articles, exchange, among others. The higher the point/marker in Figure 7 is of greater importance for the institution in this network, while the thicker and more intense the line, the narrower/more intense the cooperative relationship.

National Cheng Kung University, SINTEF Energy Research, The University of British Columbia and Norwegian University of Science and Technology are located in a highly relevant position in the field of torrefaction. Scientific cooperation between SINTEF, National Cheng Kung University and the University of British Columbia and Norwegian University of Science and Technology are also very strong and important in the development and dissemination of knowledge to other institutions in the collaboration network.

Also, it is possible to identify the pioneer institutions from the most intense color (dark blue) and see how much the field "biomass torrefaction" has gained interest in the growing number of institutions between the years 2016-2018, through the change in the intensity of colors (from green to yellow).

Between 2013 and 2019, there was an increase in the intensity of cooperation in publications, as also seen in Figure 5. It turns out that, of the total of 26 clusters generated from the database with 60 institutions, only 16 clusters were interconnected forming the component giant of the institutional collaboration network. This shows that part of the scientific activities has been carried out individually in institutional form, in most publications, indicating a wide field of inter-institutional collaborations to be developed.

### *4.3 Detection of Scientific Communities*

The possibility of identifying the most influential researchers within the clusters helps to direct a possible determination of additional emerging fields of study by capturing more recent topics proposed by these researchers (FAHIMNIA et al., 2015). According to Perea-Moreno et al. (2019) a scientific community can be defined as a set of nodes that are more densely connected with each other than with the rest of the network. In this sense, scientific communities tend to have a central nucleus cohesive with the peripheral spheres, which are the weakest links as they move away from the nucleus.

A total number of 1,894 authors will publish in the torrefaction field, according to the WoS database. In order to avoid disambiguation of the authors' names, the data were checked and corrected individually in relation to possible combinations of names represented by initials, name variations or duplication of authorship. Considering the occurrence of at least 5 publications indexed by the author, we obtain the number of 58 authors directly related to the biomass torrefaction field. Table 5 presents general information about the 10 authors who most published in indexed journals.

**Table 5**. The performance of the top 10 most productive authors.

| Author | Total Pubs | Total Citation | Total Strength | h-index[a] | Country[b] |
|---|---|---|---|---|---|
| Wei-Hsin Chen | 29 | 2540 (1°) | 29 (4°) | 27 | Taiwan |
| Oyvind Skreiberg | 27 | 636 (5°) | 47 (1°) | 14 | Norway |
| Quang-Vu Bach | 20 | 581 (7°) | 30 (3°) | 15 | Norway |
| Khanh-Quang Tran | 20 | 460 (8°) | 35 (2°) | 16 | Norway |
| Animesh Dutta | 10 | 360 (10°) | 5 (42°) | 10 | Canada |
| Prabir Basu | 8 | 161 (27°) | 8 (31°) | 9 | India |
| Maurizio Grigiante | 8 | 47 (46°) | 14 (8°) | 7 | Italy |
| Jun Li | 8 | 285 (15°) | 11 (18°) | 12 | Scotland |
| C. Jim Lim | 8 | 323 (13°) | 9 (28°) | 14 | Canada |
| Liang Wang | 8 | 112 (35°) | 13 (11°) | 19 | Norway |

[a]Obtained from publications referring to the torrefaction of biomass and energy, in the period from 2000 to 2019, with information obtained on 01/11/2020. [b]Location of the author's research institution.

The authors that most stand out for the total number of publications are: Wei-Hsin Chen, from National Cheng Kung University - Taiwan, with 29 publications; Oyvind Skreiberg, from SINTEF Energy Research - Norway, with 27 publications; Quang-Vu Bach, from the Norwegian University of Science and Technology - Norway, with 20 publications; and Khanh-Quang Tran, from the Norwegian University of Science and Technology - Norway, with 20 articles.

The author Wei-Hsin Chen is the one that stands out both in the total number of publications (29 publications) and in the number of citations (2540 citations). Significant changes are also observed when analyzing the number of publications: citation. For example, authors Oyvind Skreiberg, Quang-Vu Bach and Khanh-Quang Tran were ranked 2nd, 3rd and 4th most publications, respectively; however, in the ranking of citations they were classified in 5th, 7th and 8th position, respectively. It may be related to the impact factor of publications or the means of dissemination. For this, the h-index is based on the assumption that the number of citations received by a scientist is a better indicator of the relevance of his work than the number of articles published or the journals in which they are published. According to Hirsch and

Buela-Casal (2014) the h-index takes into account the number of articles published and the citations to these articles in a balanced way and, therefore, is more indicated in comparisons between scientists.

The collaborative relationships between authors in the field of biomass torrefaction can be better understood from the understanding that scientific communities are generally groups that relate to members of groups from other communities (MONTOYA et al., 2018). Figure 8 shows the clusters (21 clusters) and collaboration networks between the main researchers (58 authors), with at least 5 publications, and the temporal overlap of authorship. It is observed the formation of different communities publishing about biomass torrefaction, corroborating with the previously discussed that the scientific activities in this field have been carried out, in most cases, in isolated or pulverized form.

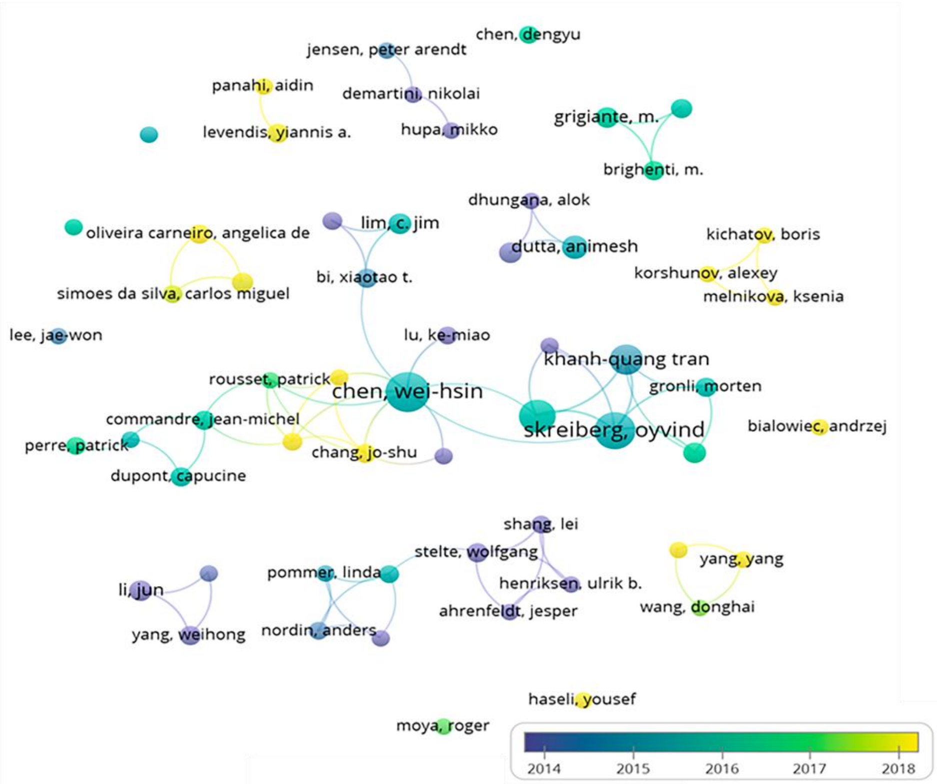

**Figure 8**. Network of authors in publications.

The existence of different groups of researchers was observed, with a large concentration of researchers in the central part of the network, a lower concentration in other regions and a set of isolated nodes disconnected from the rest of the network. The size of the nodes shows their relative frequency in the structure of the author network in Figure 8 and the width of the links illustrates the strength of the relationship between each pair. Besides, the network of authors highlights the existence of partially or totally isolated concentrations of researchers, with no connection to the centrality of the network. It appears that the average distance illustrates the level of maturity of the collaboration in the network by distance between the authors. In addition, a shorter distance means that there is a higher level of maturity in the collaboration network.

According to Fahimnia et al. (2015) the identification of the most influential researchers within the clusters helps to determine possible emerging fields of study by observing and cataloging the most recent topics addressed by these researchers. Figure 9 shows the community with only interconnected authors and the details of the clusters of this scientific community are detailed in Table 6.

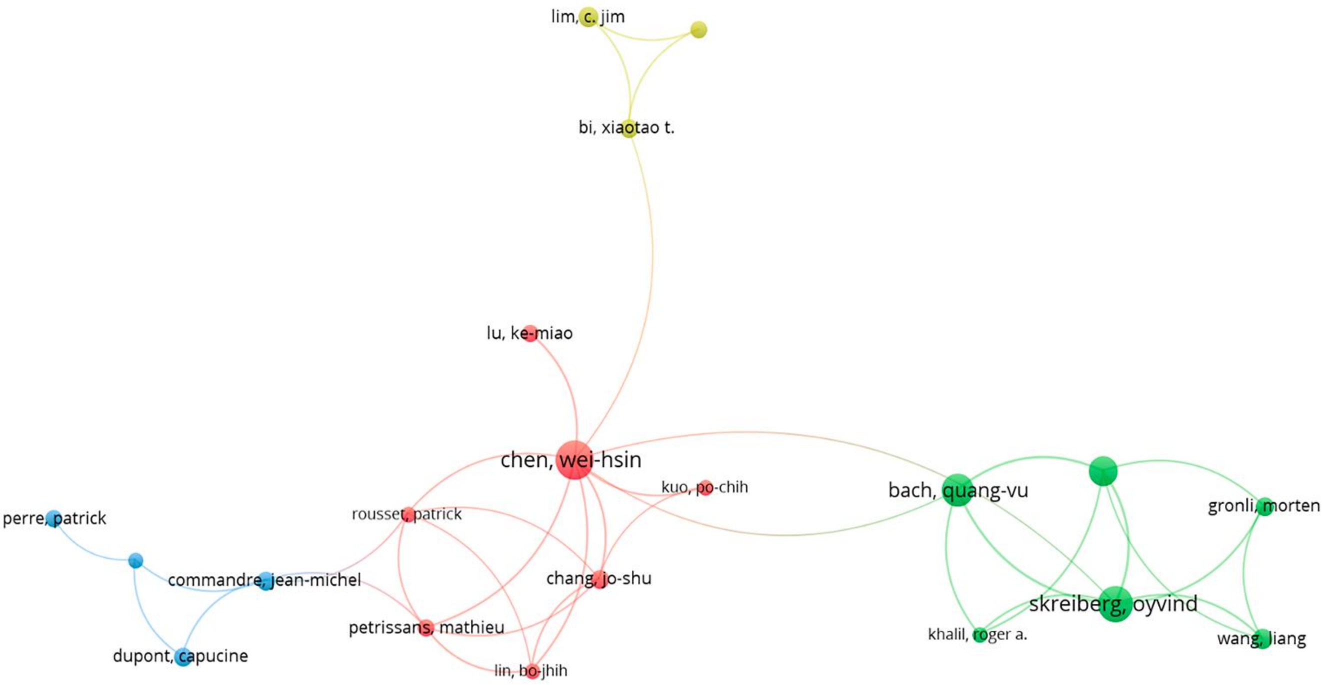


**Figure 9**. Interconnection network of authors in the biomass torrefaction publications.

**Table 6**. The author's communities in the topic biomass torrefaction.

| Cluster | Color | Authors |
|---|---|---|
| 1 | Red | Chang, Jo-Shu; Chen, Wei-Hsin; Kuo, Po-Chih; Lin, Bo-Jhih; Lu, Ke-Miao; Petrissans, Mathieu; Rousset, Patrick |
| 2 | Green | Bach, Quang-Vu; Gronli, Morten; Khalil, Roger Antoine; Khanh-Quang, Tran; Skreiberg, Oyvind; Wang, Liang |
| 3 | Blue | Commandre, Jean-Michel; Dupont, Capucine; Perre, Patrick; Salvador, Sylvain |
| 4 | Yellow | Bi, Xiaotao T.; Lim, C. Jim; Sokhansanj, Shahab |

The interconnected collaboration network (Figure 9) has 20 authors separated into 4 clusters, maintaining some level of interaction, sharing works and scientific development in the field of biomass torrefaction. The thicker the line, the greater the number and strength of this relationship. The green cluster has great centrality and strength in publications in the field of torrefaction due to the high individual performance of its main authors, forming its team and collaboration network. These researchers have strong research connections between them, which can be caused due to the geographical position and proximity of their research institutes.

In addition to what was observed in the collaboration and contribution networks of authors cataloged in WoS, in the scope of torrefaction technological development, recent advances have been gaining interest, emphasizing the use of non-conventional raw materials, improvements in the production of torrefied pellets, new applications of torrefaction products and technological advances in production processes and torrefaction systems. As an example, publications on catalytic torrefaction (ONSREE and TIPPAYAWONG, 2020, TIPPAYAWONG et al., 2019), torrefaction-gasification integration processes (BACH et al., 2019, TAPASVI et al., 2015), use of binding agents (binders) to the torrefied biomass aiming to improve the pelletization process (BAI et al., 2016, EMADI et al., 2017), biomass torrefaction as an adsorbent (CIOLKOSZ et al., 2019, DODDAPANENI et al., 2018, GAN et al., 2018), a precursor in the production of liquid biofuels (CHALUVADI et al., 2019, SHEIKH et al., 2013), use of torrefaction biomass for soil correction/improvement (HAN et al., 2017, OGURA et al., 2016) and advanced applications of torrefaction condensate (DODDAPANENI et al., 2017, PAPADOPOULOU et al., 2018). There is also the development of research related to the hybridization of technologies, such as the use of solar energy and torrefaction (CELLATOĞLU and İLKAN, 2015, CHEN et al., 2020, SWAMINATHAN and NANDJEMBO, 2016)

## 5. Final Considerations and Conclusion

Torrefaction as a pre-treatment technology for biomass was studied based on bibliometric co-authorship analysis and network analysis tools for a better systemic understanding of the research field. 662 publications were collected from the WoS database, mapped and highlighted the main collaboration networks between authors, institutions and countries. Although the database was collected from the WoS, which has a vast and comprehensive scientific collection, it is important to note that we do not have all the publications, with the possibility of significant bias in the research field, publication of reports and non-indexed documents, in addition to publications in other databases and languages. Not limited to that, complementary concepts about scientific collaboration networks and information on h-index, impact factor (JCR) and category of journals were presented.

The increase of publications on biomass torrefaction had a linear growth and with greater intensity from the year 2011, continuing to the present day. This growth trend is likely to continue in the coming years, as the international biomass market has been increasingly consolidated with the substitution of conventional coal for biocarbon, mainly in the form of pellets. The scientific community in this field of research has focused its efforts on improving processes and technologies for the production of these solid fuels.

In the period from 2000 to 2019, it was observed that the journals "Energy & Fuels", "Bioresource Technology", "Fuel", “Energy” and “Biomass & Bioenergy” were the ones that published the most about biomass torrefaction from the WoS database. The countries that are ahead in the volume of publications, based on the affiliation of co-authors, were: USA, China, Canada, France, Norway, Taiwan, South Korea and Holland. Consequently, the USA and China are at the center of the great collaboration network.

Institutional collaboration networks have been analyzed for their origin and development over the years. The institutions with the largest number of scientific publications were SINTEF and Norwegian University of Science and Technology, both Norwegian; National Cheng Kung University, Taiwanese; University of British Columbia, Canadian; Cirad, French; Technical University of Denmark, Danish and Umeå University, Swedish. Despite the existence of different groups of researchers, at the center of the scientific community is the Taiwanese author Wei-Hsin Chen, followed by Norwegians Oyvind Skreiberg, Quang-Vu Bach, and Khanh-Quang Tran.

The methodological limitation of this study is in the restriction used as to the search strategy only in the "title", being justified by the large number of publications without being related to the study when the search for "topic" (title and/or abstract and/or keywords). The possible expansion of keyword combinations is another possible limiting factor, however with the increase in the number of combinations it can result in a more exhaustive review and without significant differences with the present study.

Institutional collaboration networks showed the direction for new insights and pointed out the origin of the technological development of torrefaction. Finally, the identification of the most influential researchers within the clusters aimed to assist in determining possible emerging fields of study by observing and cataloging the most recent topics addressed by these researchers.

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