

Review

Thermal Treatment of Biomass: A Bibliometric Analysis—The Torrefaction Case

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Abstract: The aim of the paper was to summarize and discuss current research trends in biomass thermal treatment (torrefaction process). Quantitative analyses were carried out, in which the main countries, research units and scientists were indicated. The analysis showed a clear upward trend in number of publications after 2010. Most scientists on selected topics come from China, USA, Canada, South Korea, Republic of China, Poland (Web of Science—Core Collection (WoS-CC) and Scopus databases). Quantitative analysis also showed that the most relevant WoS-CC categories in the summary are: Energy Fuels, Engineering Chemical, Agricultural Engineering, Biotechnology Applied Microbiology and Thermodynamics and Scopus Subject area: Energy, Chemical Engineering, Environmental Science, Engineering and Chemistry. Thematic analysis included research topics, process parameters and raw materials used. Thematic groups were separated: torrefaction process (temp.: 150–400 °C), hydrothermal carbonization process (HTC) (temp.: 120–500 °C), pyrolysis process (temp.: 200–650 °C) and gasification and co-combustion process (temp.: 350–1600 °C). In the years 2015–2019, current research topics were: new torrefaction technologies (e.g., HTC), improvement of the physico-mechanical, chemical and energetic properties of produced fuel as well as the use of torrefied biomass in the process of pyrolysis, gasification and co-combustion. The raw materials used in all types of biomass thermal treatment were: energy crops, wood from fast-growing and exotic trees, waste from the agri-food industry, sewage sludge and microalgae.

Keywords: torrefaction; hydrothermal carbonization; pyrolysis; gasification; bibliometric analysis; research trends; research topic; scientometric; solid biomass



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1. Introduction

In recent years, there has been an increase in population around the world. This clearly affects the increase in energy consumption [1,2]. Most energy comes from the burning of fossil fuels, which is associated with the emission of large amounts of greenhouse gases [3]. Therefore, a reduction in the usage of fossil fuels is needed. There should be an increase in participation of renewable energy sources (RES) in general energy balance [4].

In the European Union (EU) policy climate issues play an important role. An element of EU's energy policy is “2020 climate & energy package” so-called “three 20 targets” (20% improvement in energy efficiency reduction greenhouse gas emissions, 20% of EU energy from RES, 20% improvement in energy efficiency), voted through by the European Parliament in 2008. It is a collection of acts aiming to ensure the achievement of EU objectives regarding counteracting the climate change. One of the objectives is increasing the share of RES up to 20% to 2020 [5,6].

The need to reduce the consumption of fossil fuels, greenhouse gas emissions and increase the expenditure on renewable energy has increased the interest of researchers in

the subject of RES. Increasing demands regarding the protection of natural environment and the increasing demand for energy caused greater interest in RES which use biomass, sun, wind, water, sea and geothermal energy. This caused an intensive development of scientific research towards RES [7]. In Poland such research mainly regards RES using biomass, solar energy and wind energy. There are also researches regarding the energetic use of waste.

Numerous studies have showed that biomass has the greatest energy potential from all RES sources. Technologies for the processing and energy use of biomass can be applied in developing and developed countries [8,9]. In EU an directive has been taken in regarding biofuels (2015/1513) which promotes the use of renewable biofuels in EU Member States [4]. There is an increase in researchers' interest in issues related to the production of biofuels from biomass, e.g., from energy crops, agricultural waste, etc. [10,11]. In Poland in 2014 76% of energy from RES originated from solid biomass [6]. Biomass can be a raw material for the production of liquid biofuel, gaseous biofuel and solid biofuels [11,12] (Figure 1).

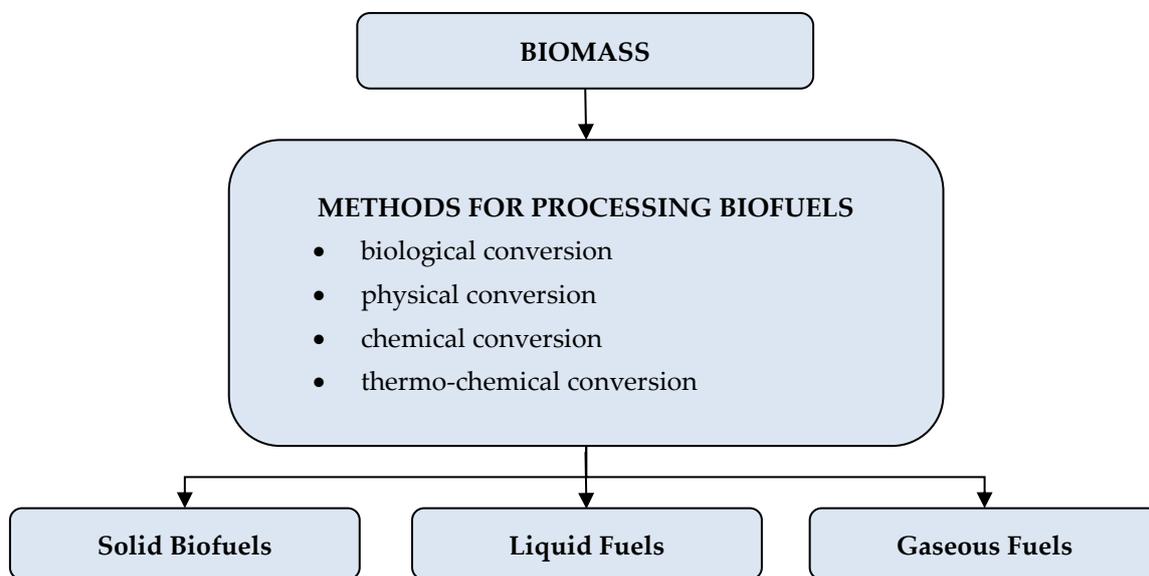


Figure 1. Classification of biofuels.

In order to meet the demand of the global energy market, research is ongoing on the search for new sources of biomass. These include: wood from eucalyptus and bamboo, energy crops, agricultural waste, agricultural and food industry waste, municipal waste, sewage sludge, etc. [6,8]. The use of lignocellulosic biomass of energy crops, e.g., miscanthus, willow, poplar, acacia or paulownia as a source is particularly interesting [7,11,13].

According to current trends in research on solid biofuels presented by Knapczyk et al. [12] main groups of topics are: (1) searching for new raw materials for the production of solid biofuels—e.g., waste biomass from palm oil [14], sunflower husks [15], peanut shells [16], new species etc. [17,18], (2) optimization of the supply chain, warehouse logistics and biofuels legislation, e.g., development of an identification system to ensure the quality of biomass [19], legal analysis of the international standard classification of solid biofuels etc. [20] (3) optimization of plant cultivation, study of physicochemical properties of raw materials—e.g., determining the calorific value, chemical composition of elements and main energetic parameters in wood and bark of fast growing trees [21–26] and herbaceous etc. [27], (4) agglomeration process—e.g., assessment of physico-mechanical properties of agglomerate and the effect of added biochar and bio-oil etc. [10,28–32], (5) the torrefaction process—biomass torrefaction [33–38], hydrothermal waste carbonization, wood mixtures etc. [39,40] and the remaining group, in which the authors raised topics such as composition testing and combustion modeling in household.

Methods for processing biofuels can be divided into: biological conversion, physical conversion, chemical conversion and thermo-chemical conversion. These methods are used to improve the physico-mechanical and chemical parameters of biofuels. The resulting products have various applications, such as biofuels, agglomeration, fertilization, soil remediation and many more [41–44]. As a result of processing, the products can be used directly or serve as a raw material for further processing.

One of the main methods for processing solid biofuels is thermal processing. Depending on the temperature used the thermal processes can be divided into drying, torrefaction, pyrolysis and gasification (Figure 2). Each of these processes has different products and intermediates. With increasing temperature, energy parameters may increase, but this is associated with increased energy expenditure. Thermal biomass treatment can improve energy, physico-mechanical and chemical properties. The parameters of individual processes may vary depending on the temperature, atmosphere and exposure time. The efficiency of the process is also influenced by the raw material parameters (humidity, degree of comminution, etc.) [45,46].

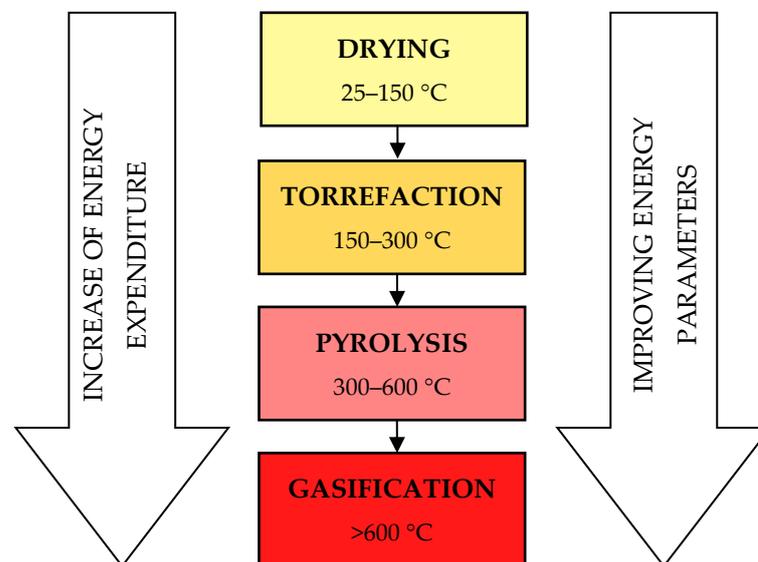


Figure 2. Biomass thermal treatment—processes and range of temperatures.

The thermal process with absence of air, is called pyrolysis. In the literature often the name is related to the process temperature. Low temperature range (150–300 °C) is characteristic of the torrefaction and above 300 we have the right pyrolysis. This processes are both endothermic one, so energy needed to be supplied for the process [47–49].

Bibliometrics is a collection of mathematical and statistical tools used for objective assessment of scientific achievements. This term was used for the first time in 1969 by A. Pritchard [50]. Bibliometric analysis allows to highlight current research topics [12,51–55], observing scientific trends in the world and in the selected country [56,57]. It gives the opportunity to evaluate scientific units, journals, researchers based on selected parameters [58]. Using bibliometric techniques, it is also possible to indicate a network of connections between authors, countries, research topics. Data for bibliometric analysis should come from reputable and widely recognized databases of scientific publications and patents, such as Web of Science, Scopus. The main quantitative indicators include: the number of publications, number of citations, Impact Factor and Hirsch index.

The aim of the research was to determine the main research topics in the area of the use of thermal processing (torrefaction process) of biological materials and to indicate process parameters and raw materials.

2. Materials and Methods

The research was carried out using the authors' methodology [12,55,59,60] using bibliometric techniques (Figure 3).

The analyzes were divided into two stages:

I—quantitative analysis,

II—qualitative—thematic analyses.

The first stage involved searching for indexed documents in the Web of Science—Core Collection (WoS—CC) and Scopus database. The search period covered the years 1945–2019 in English. TOPIC documents were searched: “torrefaction*”, type: article.

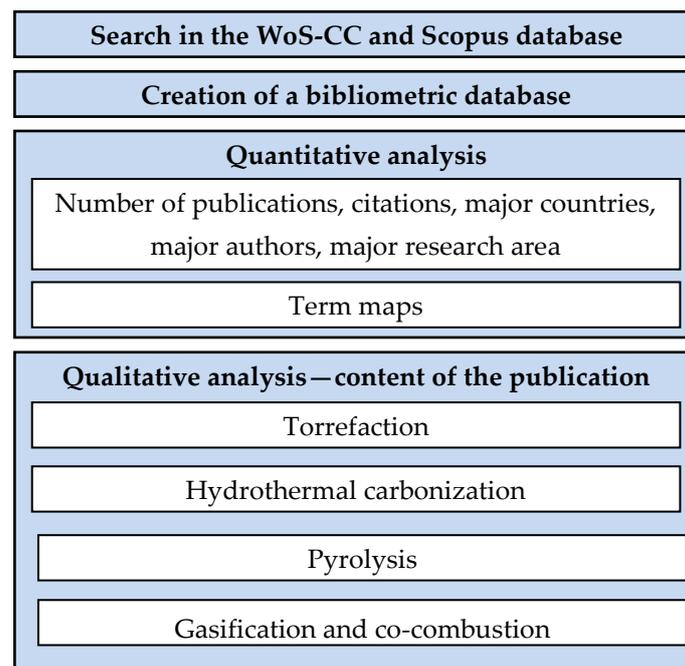


Figure 3. Diagram of research methodology.

Then bibliometric data (authors, title, year of issue, key words, additional key words, publishing house) was downloaded and quantitative analyses were performed. As part of them, the number of publications in years, number of publications in countries, leading scientists and main research centers dealing with biomass thermal treatment were shown. WoS-CC categories and Scopus Subject area were also indicated, which thematically concerned the publications.

The next stage was the analysis of keywords of the authors of the publication which were analyzed in the VOSviewer program. This program is free and is used to visualize bibliometric networks. The analyses may concern authors, keywords, journals, and others. Generated thematic maps can be created on the basis of the frequency of occurrence of keywords in years, citations, networks and others. All documents analyzed concerned the WoS-CC Energy Fuels category and Scopus Energy. Maps of terms were generated, which were used to analyze the frequency of occurrence of keywords in years and most often cited. Such maps allow to indicate current research topics and trends changes in years.

The last stage consisted of a detailed thematic analysis of the publication in the Open Access license for the entire WoS-CC: Energy Fuels category and Scopus Subject area: Energy. Open Access documents are widely available. This is especially important for industry. It makes it possible to use research results and implement selected technologies processes and process parameters in production Titles, keywords, abstracts as well as full publication texts were analyzed. The goal was to indicate process parameters, materials used for torrefaction and applications of this process. The analyzed publications were

divided into three categories according to the technology used: (1) Torrefaction, (2) Hydrothermal carbonization (HTC), (3) Pyrolysis, (4) Gasification and co-combustion. The other group contains publications that focused on related topics. In each of the groups it is specified: application, process parameters and raw materials used in the biomass thermal treatment process.

3. Results

3.1. Quantitative Analysis Results

The search resulted in 1564 scientific articles published in journals in WoS-CC database and 1231 documents in Scopus. Among the found publications, 318 (WoS-CC) and 188 (Scopus) were published under the Open Access license. The oldest publication on torrefaction dates from 1919 and is entitled: Article on the theory of drying and torrefaction [61].

The most cited publications in WoS-CC and Scopus databases include:

- Bridgeman T.G. et al.—Total Citations: 474 WoS-CC/545 Scopus [62],
- Phanphanich M. and Mani S.—Total Citations: 432 WoS-CC/512 Scopus [63],
- Arias B. et al.—Total Citations: 427 WoS-CC/504 Scopus [64].

Figure 4 shows the distribution of the number of all publications indexed in WoS-CC and Scopus database. The years 2005–2019 were chosen to increase readability. A clear upward trend has been visible since 2010.

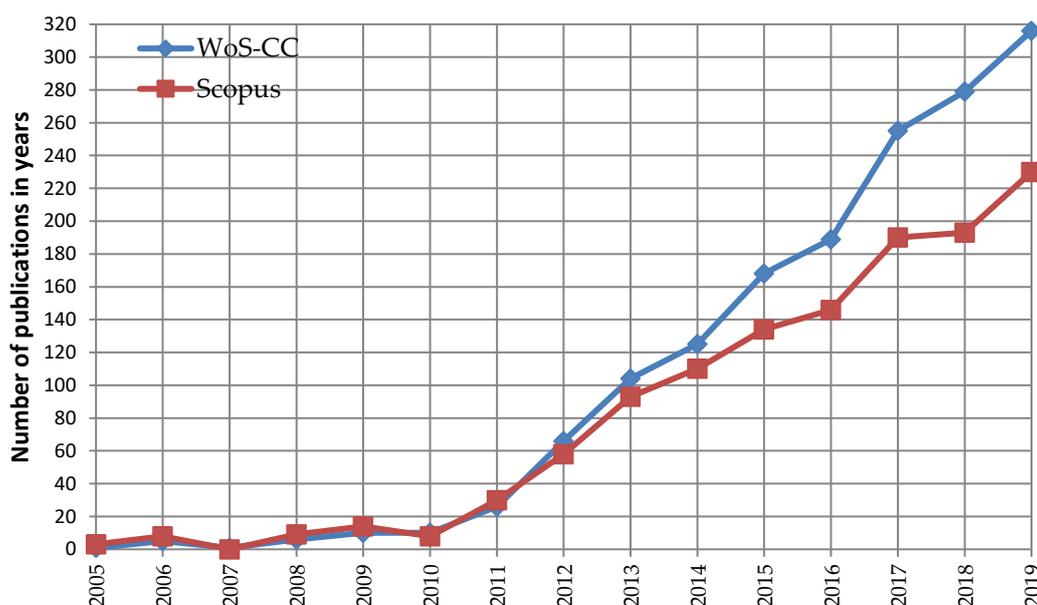


Figure 4. Number of articles in years indexed in WoS-CC and Scopus—2005–2019.

Figure 5 shows the distribution of the number of publications with Open Access license indexed in WoS-CC and Scopus database. The years 2005–2019 were chosen to increase readability. A clear upward trend has been visible since 2010.

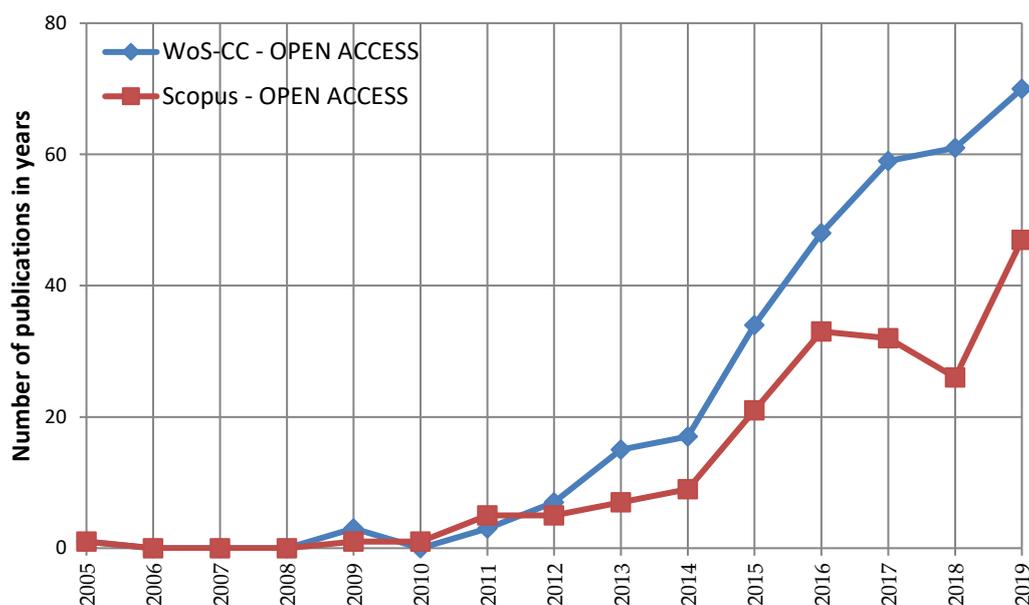


Figure 5. Number of articles in years indexed on WoS-CC and Scopus with Open Access license—2005–2019.

Table 1 shows the number of publications indexed in the WoS-CC and Scopus databases. It can be seen that in both cases most publications were published in Asia (China, South Korea, Republic of China), North America (USA, Canada), Europe (France, Poland).

Table 1. Number of articles in years indexed in WoS-CC and Scopus in countries.

WoS-CC	Number of Articles	Scopus	Number of Articles
China	318	China	221
USA	289	USA	207
Canada	116	South Korea	84
Republic of China	95	Canada	82
France	72	Republic of China	75
South Korea	71	Poland	62
Poland	69	France	57
Sweden	63	Malaysia	55
Japan	62	Brazil	50
Malaysia	62	Italy	50

Figure 6 shows the distribution of publications in the years for the 5 most relevant categories of Web of Science for the analyzed subject. Selected categories are: Energy Fuels (1059 doc.), Engineering Chemical (611 doc.), Agricultural Engineering (276 doc.), Biotechnology Applied Microbiology (267 doc.) and Thermodynamics (188 doc.). It can be seen that after 2009 there is an upward trend for all WoS-CC categories. The largest increase and also the largest total number of publications is in the Energy Fuels category.

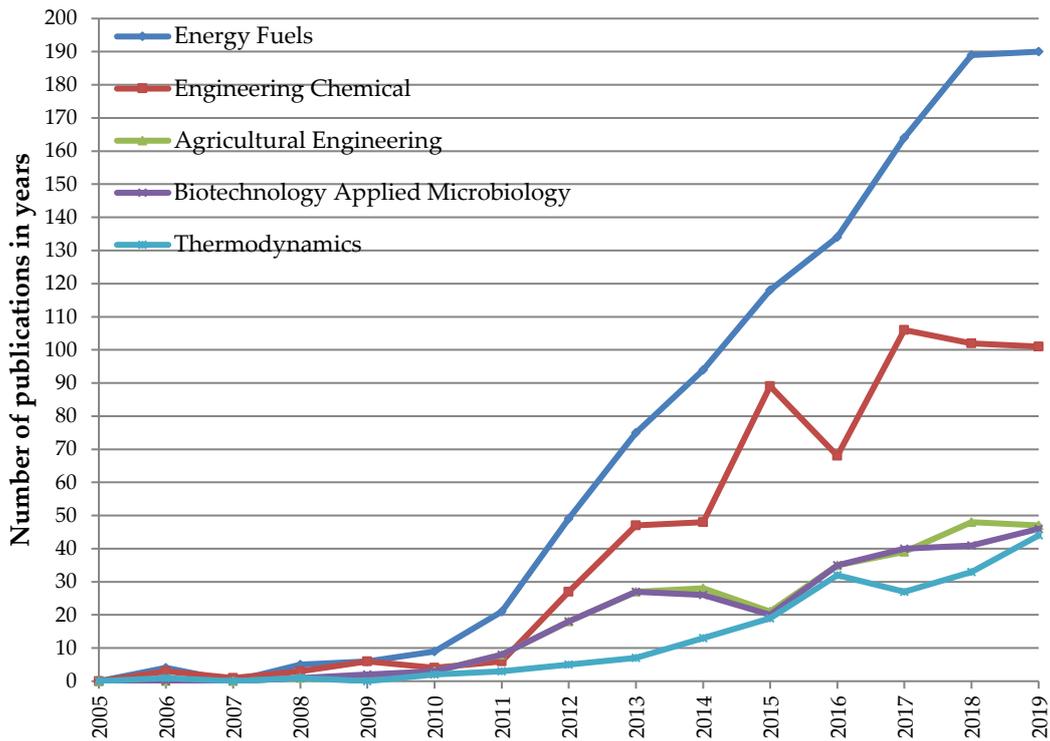


Figure 6. Number of articles in years indexed in WoS-CC in relation to the Web of Science category—2005–2019.

Figure 7 shows the distribution of publications in the years for the 5 most relevant Subject area in Scopus. Selected categories are: Energy (763 doc.), Chemical Engineering (528 doc.), Environmental Science (500 doc.), Engineering (301 doc.) and Chemistry (236 doc.). It can be seen that after 2010 there is an upward trend for all Subject area. The largest increase and also the largest total number of publications is in Energy Subject area.

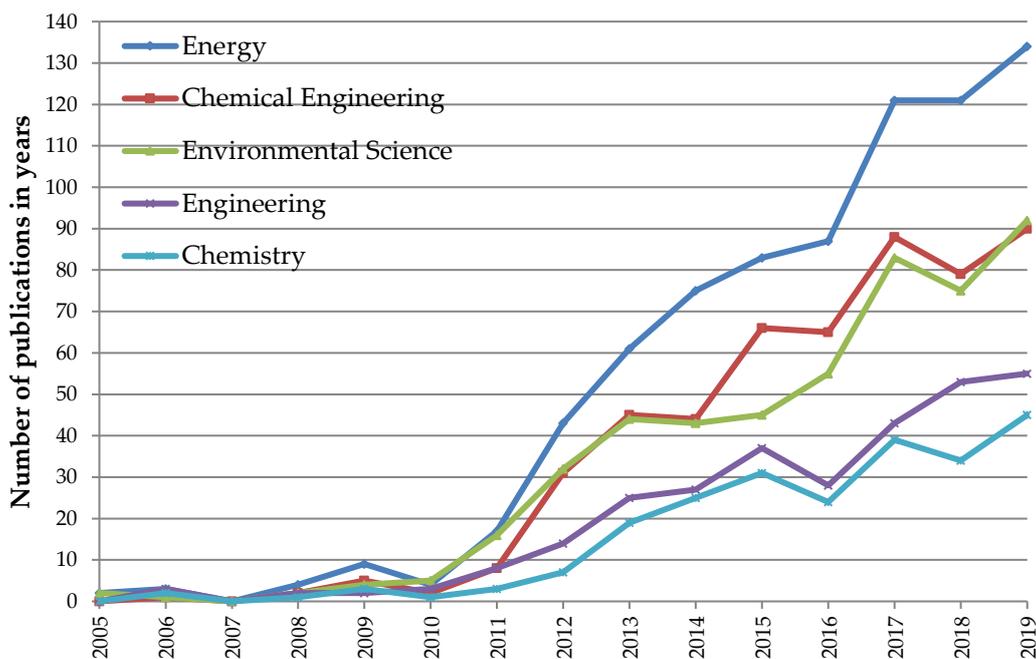


Figure 7. Number of articles in years indexed in Scopus in relation to the Subject area—2005–2019.

The next stage was the keyword analysis for 2015–2019. Such analysis allows visualizing the relationships between keywords as well as analyzing these words over a selected period. In turn, keyword citation analysis allows to identify research topics of greatest interest to researchers

The first analysis concerned the incidence of keywords in years (Figure 8.). The colors represent individual years. 2015–2016 (dark blue/blue/light blue)—‘torrefaction’, ‘biomass’, ‘biochar’, ‘pyrolysis’, ‘combustion’, ‘biochar’, ‘pretreatment’, ‘kinetics’. 2017 (green)—‘hydrothermal carbonization’, ‘wet torrefaction’, ‘fast pyrolysis’, ‘carbonization’, ‘co-combustion’, ‘slow pyrolysis’, ‘bioenergy’, ‘wood pellets’, ‘gasification’. 2018–2019 (yellow/orange/red)—‘fuel properties’, ‘rice husk’, ‘sewage sludge’, ‘torrefied biomass’, ‘biocoal’, ‘bio-oil’. One can notice the transition from torrefaction, pyrolysis, biomass combustion, analysis of selected parameters of biomass heat treatment processes, through new technologies (HTC), and ending with the search for new materials for torrefaction, e.g., sewage sludge, optimization of process parameters, testing of selected fuel properties.

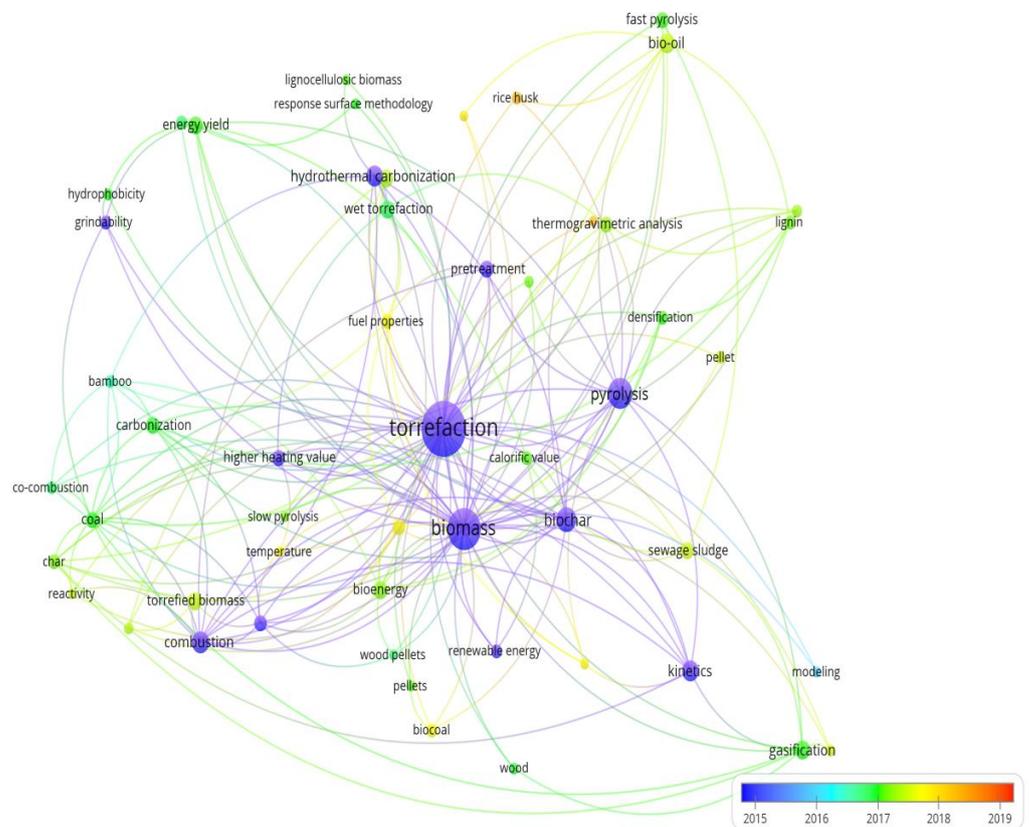


Figure 8. Map of term words for individual years—2015–2019.

The second thematic map (Figure 9) concerns the analysis of citations covered by topics/keywords. The closer the keywords are to orange/red, the higher the number of citations. The most recent keywords are: ‘bioenergy’, ‘wood pellets’, ‘wet torrefaction’, ‘hydrothermal carbonization’, ‘hydrophobicity’, ‘densification’, ‘co-combustion’. It can be stated that in the presented period (2015–2019), current research topics are new torrefaction technologies, such as HTC, research on improving the physico-mechanical and energy properties of produced fuel and the use of torrefied biomass in the pyrolysis and co-combustion process.

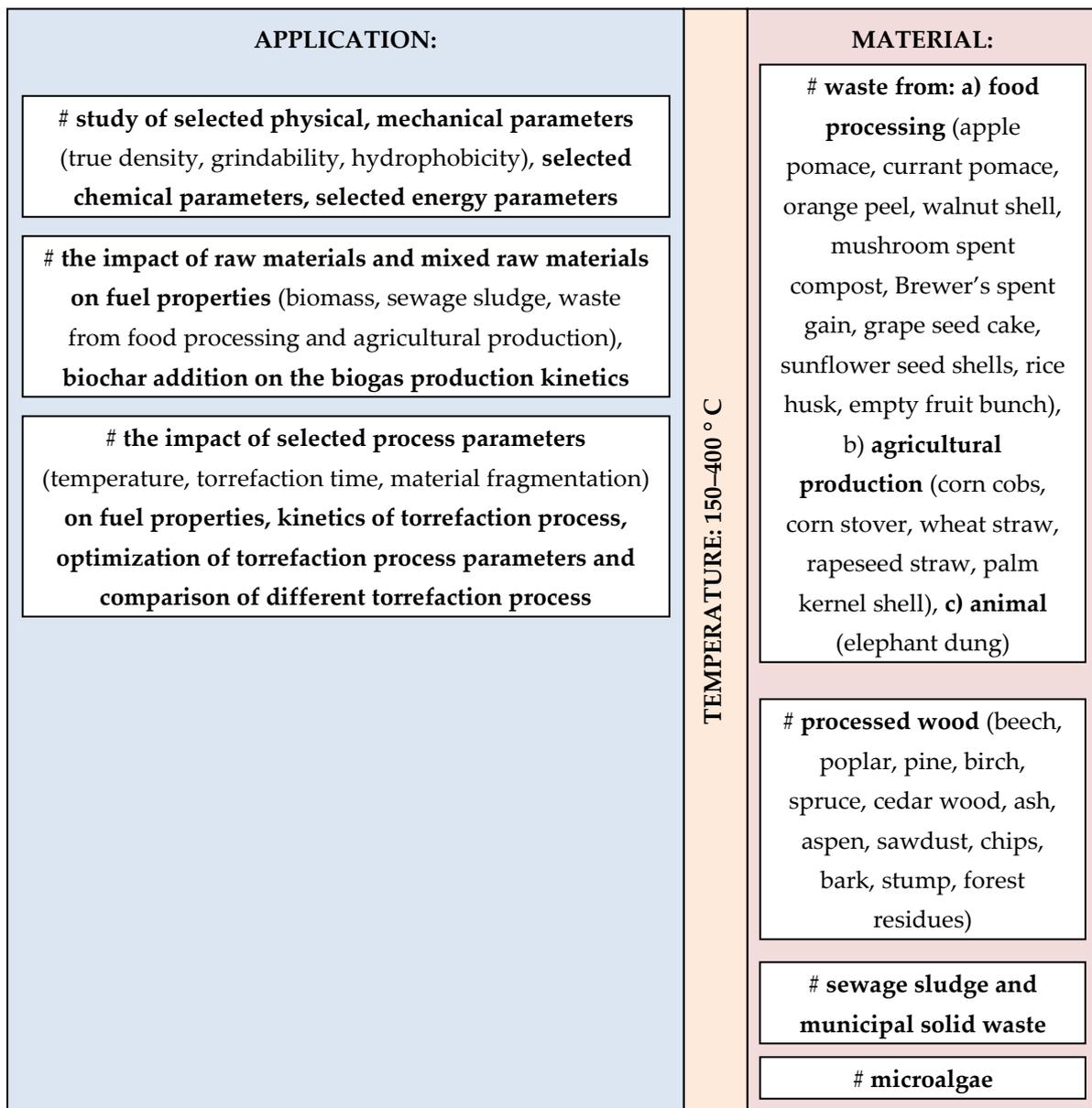


Figure 10. Main research topics and process parameters—torrefaction process.

The second group concerned the hydrothermal carbonization (HTC) process and is presented in Figure 11 and Appendix A: Table A2. There are 10 publications in this group.

APPLICATION:	TEMPERATURE: 120–500 ° C	MATERIAL:
# impact of raw material / mixtures of raw materials, process parameters on improving fuel properties		# waste from: a) food processing (rotten apple, apple pomace, apple juice pomace, grape pomace, olive cake), b) agricultural production (corn stover, off-specification compost)
# examination of selected physical, mechanical, chemical and energetic properties of HTC product		# processed wood (wood, beech wood, loblolly pine, slash pine, spruce, birch)
# impact of HTC on the char reactivity of biomass		# sewage sludge
# evaluation of hydrochar from lignin hydrous pyrolysis to produce biocokes after carbonization		
# process design, modeling, energy efficiency and cost analysis hydrothermal carbonization of waste biomass		

Figure 11. Main research topics and process parameters—the hydrothermal carbonization (HTC).

The third group concerned the use of torrefied biomass in the pyrolysis process (Figure 12, Appendix A: Table A3). There are 19 publications in this group.

APPLICATION:	TEMPERATURE: 200–650 ° C	MATERIAL:
# studies of selected physico-mechanical, chemical and energy parameters		# waste from: a) food processing (food waste, citrus waste), b) agricultural production (compost, feed)
# influence of pretreatment, kinetic study on the pyrolysis process		# biomass: a) processed wood (pine, softwood bark, softwood lumber waste, cherry wood, ash, spruce, mixed waste wood, red oak, pine, sawdust, chips, aspen, lumber, debarked logs, bark, foliage, douglas-fir, birch, oak), b) energy crops (willow, rye grass, switchgrass), c) processed wood from exotic plants (rubber tree)
# influence of pyrolysis process parameters, raw material / mixtures of raw materials, comparison of different pyrolysis technologies, modeling and optimization of pyrolysis process parameter on fuel properties		# sewage sludge

Figure 12. Main research topics and process parameters—pyrolysis group.

The fourth group concerned the use of torrefied biomass in the gasification and co-combustion process (Figure 13, Appendix A: Table A4). There were 25 publications in this group.

APPLICATION:	TEMPERATURE: 350–1600 ° C	MATERIAL:
# impact of pretreatment, raw materials / raw material mixtures / coal, torrefaction on the process performance on pyrolysis, gasification and combustion		# waste from: a) food processing (palm kernel shell, avocado pit, olive stone, grape, olive pomaces, cocoa shell, sugarcane bagasse, oil palm, chestnut, shell), b) agricultural production (wheat straw, olive tree pruning, Virginia mallow, rice straw, cassava stalks, corn cob)
# comparison of different gasification technologies		
# influence of gasification process parameters, kinetic study, modeling and optimization on fuel properties		
# design, optimization and energetic efficiency of producing hydrogen-rich gas from biomass steam gasification		
# characterizes the oxidation properties biomass char and compare with that of raw biomass char		# biomass: a) processed wood (spruce bark, spruce, ash, pine wood, pine sawdust, birch, healthy pine, beetle kill pine), b) energy crops (miscanthus, willow, napier grass), c) processed wood from exotic plants (eucalyptus, bamboo), d) other biomass (road side grass)
		# sewage sludge

Figure 13. Main research topics and process parameters—gasification and co-combustion.

The last group concerned the other topics related to the process of thermal biomass processing, which thematically did not fit directly into the previously mentioned (Figure 14, Appendix A: Table A5). There were 35 publications in this group.

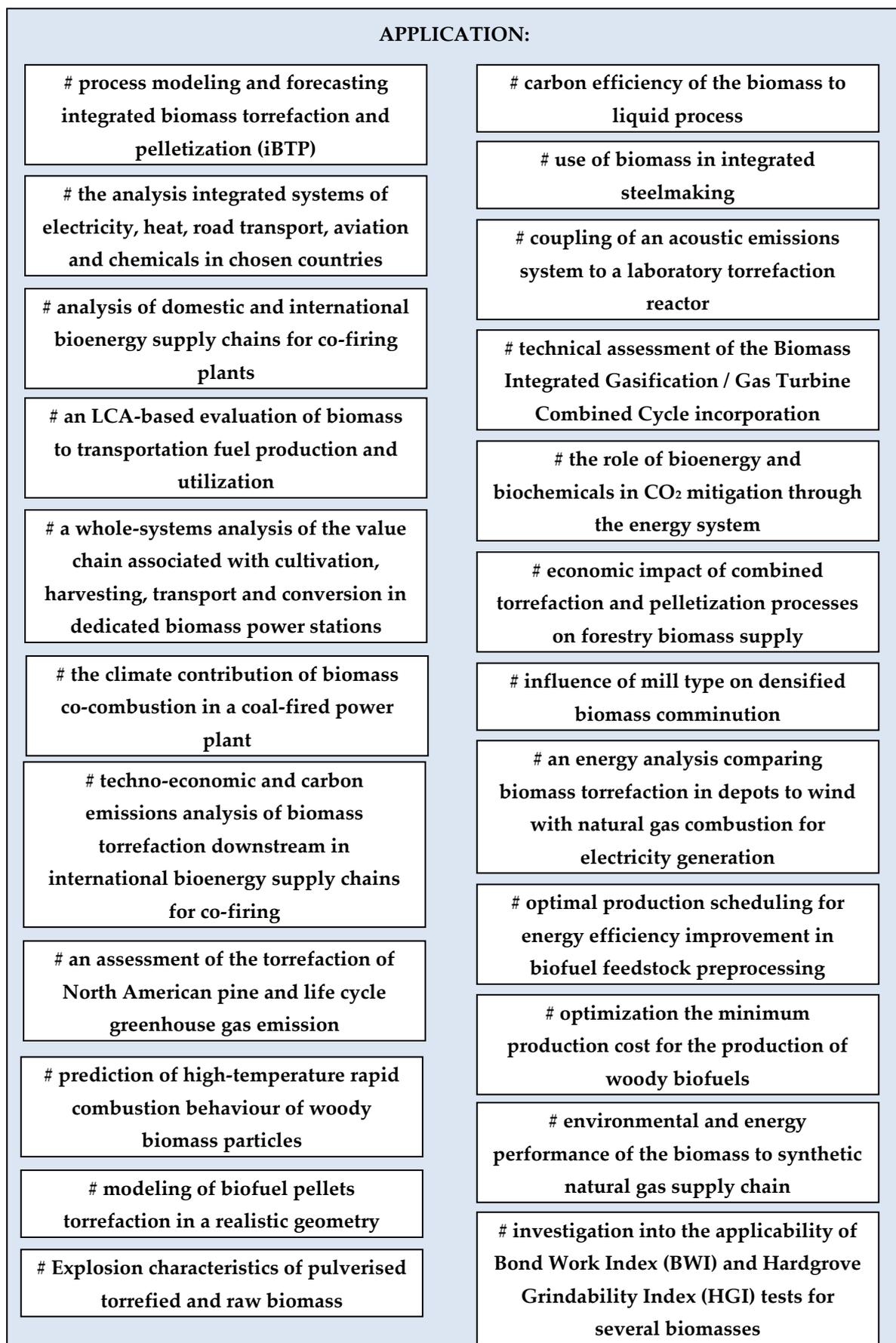


Figure 14. Main research topics—other topics.

4. Discussion

Originally, the analysis of the literature was to be carried out within the torrefaction process area. In the course of a thorough analyses, it turned out that the various thermal biomass conversion processes appear together with torrefaction. It is therefore not possible to analyse their content without taking into account other thermal processes.

Quantitative analysis showed a clear upward trend in the number of publications after 2010 (all publications and in the Open Access license), as presented in Figures 4 and 5. The trends of the graphs indicate that the number of publications may be expected to increase significantly in the following years. At the stage of quantitative analysis, it is difficult to determine unambiguously what is the maximum ceiling for this parameter. A detailed qualitative analysis should bring us significantly closer to this answer. At this stage there are no significant leaders in these topics, but there are some regions that seems to most active at this field. Most scientists studying the selected topics come from China, USA, Canada, South Korea, Republic of China, Poland (WoS-CC and Scopus databases) as presented in Table 1. Interestingly, categorization according to WoS-CC shows various publication profiles (Figure 6). This indicates that the interest is not only in the fields of energy fuels or chemical engineering, but also in other branches, like agriculture, biotechnology, or microbiology. As the Scopus categorization gives similar results (Figure 7), this could be a very promising direction for research into these processes, not just in the fuel context. Importantly, the analysis of the keywords also indicated a change in the context of the use of the term torrefaction. Initially (2015–2017), it tended to appear in the context of pyrolysis and combustion, but in later years (2017 to 2019), it also appears in the context of new technologies such as HTC and also co-firing. The newest papers also cover waste and sewage sludge treatment

A significant progress in the number of publications on this subject is directly related to the increased interest of scientists working in the thermal processing field, not only of biomass, but also of other materials, including waste. The properties of biocarbon can also be an important catalyst for the interest of the scientific world. Over the years, the possibilities for using this product have increased significantly, and new possibilities are constantly emerging. This covers with increasing interests on this topics in other branches.

As a result of qualitative (thematic) analysis, a clear upward trend was demonstrated in the thematic groups: torrefaction and gasification and co-combustion (Figure 15). The main applications of biomass heat treatment in selected groups are:

- Torrefaction process (Figure 10, Appendix A: Table A1)—The authors mainly discussed topics such as the impact of torrefaction on the hydrophobic properties of fuel, analysis of chemical, energy, physico-mechanical parameters of biochar, kinetics of the torrefaction process, influence of torrefaction process parameters on the energy properties of fuel, the impact of biogas on the efficiency of anaerobic digestion, the impact of raw material/mixtures of raw materials on the effectiveness of the torrefaction process, the effect of addition of biochar on the agglomeration process, mass and energy balance analysis in a continuous torrefaction installation, optimization of torrefaction process parameters, comparison of different technologies used in the torrefaction process, comparison of selected properties of biochar to coal. The process temperatures ranged from 200–400 °C. The materials used in torrefying were biomass of various origins. The main sources of biomass were: energy crops, wood from fast growing and exotic trees with varying degrees of processing, mixtures of torrefaction and biomass, agricultural waste, food industry waste, sewage sludge and microalgae.
- HTC process (Figure 11, Appendix A: Table A2)—The authors mainly discussed topics such as the impact of HTC on improving fuel energy properties, the impact of raw material and parameters on process efficiency, modeling and optimization of the HTC process, the impact of HTC on reactivity and combustion kinetics. The process temperatures were in the range of 120–500 °C. The materials used in the hydrothermal carbonization process were biomass of various origins. The main sources of biomass

- were energy crops, wood with various degrees of processing, agricultural waste, food industry waste and sewage sludge.
- Pyrolysis process (Figure 12, Appendix A: Table A3)—The authors mainly discussed topics such as the impact of process parameters (temperature, time) on the chemical, energy and physical-mechanical properties of fuels, kinetic analysis of the pyrolysis process, production and characterization of bio-oil and biochar, activated carbon from the pyrolysis, biochar characteristics from biomass carbonization, process optimization. Process temperatures were in the range: 200–650 °C. Materials used in torrefaction were biomass of various origin. The main sources of biomass were energy crops, wood with varying degrees of processing from fast-growing, fruit and exotic trees, agricultural waste, food industry waste and sewage sludge.
 - Gasification and co-combustion process (Figure 13, Appendix A: Table A4)—The authors mainly discussed topics such as analysis of the kinetic process, process efficiency (proliferation, gasification, combustion), analysis of the co-combustion process of mixtures, e.g., sewage sludge, coal with biomass (biochar, raw), the impact of material changes (torrefaction, mixing of various raw materials) on the chemical, energy and physico-mechanical properties of fuels, process optimization. Process temperatures were in the range: 350–1600 °C. Materials used in torrefaction were biomass of various origins. The main sources of biomass were energy crops, wood with varying degrees of processing from fast-growing, fruit and exotic trees, agricultural waste, food industry waste and sewage sludge. Blends of biomass with coal were also used.

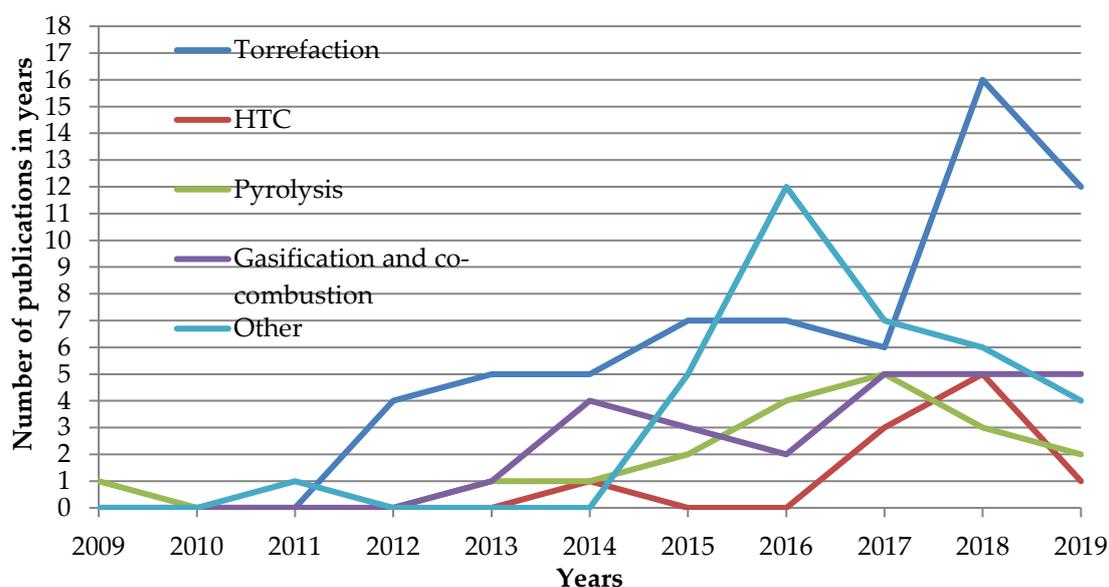


Figure 15. Number of articles in years in individual thematic groups.

Publications that did not fit thematically in the groups: torrefaction, HTC, pyrolysis, gasification and co-combustion were placed in the “other” group (Figure 14, Appendix A: Table A5). The main topics included regional analysis and global effectiveness of the use of torrefaction and biochar in the bioeconomy, analysis and optimization of the solid biofuels supply chain, analysis of integrated energy generation systems (biomass gasification, gas turbine and others) in selected areas of the economy, product life cycle analysis (LCA), technical and economic analyzes of the biomass torrefaction process in selected countries, optimization of production scheduling, forecasting and modeling of biomass thermal treatment processes, investigation into the applicability of the Bond Work Index (BWI) and Hardgrove Grindability Index (HGI) tests for several biomasses.

To date, many review publications have been created covering a selected thematic area (67 documents—WoS-CC, 57 documents—Scopus). These articles are published in leading journals, and their usefulness is demonstrated by a large number of citations. Examples of thematic areas discussed: improvement of selected properties through the torrefaction process, analysis of the technologies used, indication of application areas [65,66], application of thermochemical conversion for selected biological materials [67,68], co-combustion of coal with biomass, as well as biomass pretreatment in selected countries [69]. The results of this publication complement the current literature research with a comprehensive review of publications in the Open Access license in the scientific databases WoS-CC (WoS-CC category: Energy Fuels) and Scopus (Subject area: Energy).

All this information shows clearly that thermal processing of biomass, and in particular torrefaction is a promising technology, and in the next few years we can expect to see many papers about this process. Qualitative analysis shows that at this time, we cannot precisely forecast what the trends in the next years will be. For sure papers concerning torrefaction will more concentrated on the other branches than energy and fuels. Microbiology seems to be promising way, as trend analysis (Figures 6 and 7) shows potential to improvement in this category. Also production and biochar analysis seems to be still a very desired direction. Introduction of new materials, like waste biomass, or sewage sludge, seems to be next stage in research list of many scientists. As this topic is still new, there is big potential for good papers, which valuable will be evidenced by high citation scores.

Thanks to the holistic approach and cumulative presentation of results, this publication can be a valuable source of knowledge for researchers dealing with selected topics and industry. Especially in the latter area, trade and scientific magazines in the Open Access license are important because they can be an inspiration to implement innovative solutions and establish scientific cooperation.

5. Conclusions

- (1) Thermal biomass processing is a current research topic. A clear upward trend in the number of publications after 2010 can be noticed. Quantitative analysis also showed that the most important categories of WoS-CC in the selected topic are: Energy Fuels, Engineering Chemical, Agricultural Engineering, Biotechnology Applied Microbiology and Thermodynamics and Scopus Subject area: Energy, Chemical Engineering, Environmental Science, Engineering and Chemistry.
- (2) In 2015–2019, current research topics were: new torrefaction technologies (e.g., HTC), improvement of the physico-mechanical, chemical and energy properties of the fuel produced and the use of torrefied biomass in the processes of pyrolysis, gasification and co-combustion.
- (3) The raw materials used in all types of heat treatment processes were energy crops, wood from fast-growing and exotic trees, waste from the agri-food industry, waste from agricultural production, sewage sludge and microalgae.

The thematic scope of the analyzed publications was very diverse. Four main thematic groups were identified: torrefaction process, HTC process, pyrolysis process and gasification and co-combustion process. In addition to research topics related to process analysis and optimization, improvement of chemical, energetic and physical-mechanical properties of fuel, properties of raw materials and their mixtures, the authors also discussed the topics of technical and economic analysis of the torrefaction process, LCA, analysis and optimization of the supply chain and investigation into the applicability of Bond Work Index (BWI) and Hardgrove Grindability Index (HGI) tests for several biomasses.

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Appendix A

Table A1. Torrefaction process—detailed thematic analysis.

Ref.	Year	Application	Process Temp. (°C)	Material
[70]	2019	- influence of the temperature of the torrefaction on the hydrophobic properties of waste biomass	200, 220, 240, 260, 280, 300	apple pomace, currant pomace, orange peel, walnut shell, pumpkin seeds
[71]	2019	- fuel characteristics of biochars from torrefaction (a.k.a., roasting or low-temperature pyrolysis) of elephant dung (manure)	200, 220, 240, 260, 280, 300	elephant dung (manure)
[72]	2019	- fuel characteristics of biochars from torrefied wood sawdust in normal and vacuum environments	200, 220, 240, 260, 280, 300	wood sawdust
[73]	2019	- production of wood pellets mixed with torrefied rice straw	220, 280	wood pellets mixed with torrefied rice straw
[74]	2019	- production of hybrid sewage sludge fuel for the effective management of sewage sludge	250	sewage sludge
[75]	2019	- concept of spent mushrooms compost torrefaction-studying the process kinetics and the influence of temperature and duration on the calorific value	200–300	mushroom spent compost
[76]	2019	- physical and chemical properties, true density, grindability and hydrophobicity of Thar coal along with raw and torrefied corn cob were investigated	200, 225, 250, 275, 300	corn cobs
[77]	2019	- effects of automatic temperature control in torrefaction and the use of additives in pelletization	250–320	wood chips from Japanese cedar
[78]	2019	- the effect of biochar addition on the biogas production kinetics from the anaerobic digestion of brewers' spent grain	200–300	Brewer's spent grain
[79]	2019	- kinetics of torrefaction and determine the effects of process temperature on fuel properties of torrefied products (biochars)	200–300	Sewage sludge
[80]	2019	- a fundamental research on synchronized torrefaction and pelleting of biomass	200	Corn stover, big bluestem
[81]	2019	- the concept of carbonized refuse-derived fuel (CRDF) by refuse-derived fuel (RDF) torrefaction	200–300	RDF
[82]	2018	- impact of biomass diversity on torrefaction process	200–300	ash-wood, beech, poplar, willow, pine, pine forest residues, scot pine bark, miscanthus, reed canary grass, corn cob, grape seed cake, sunflower seed shells, wheat straw (French), wheat straw (Swedish)
[83]	2018	- ultrasonic pelleting of torrefied biomass for bioenergy production	200–300	wheat straw
[84]	2018	- energetic properties of torrefied and raw wheat straw, rapeseed, and willow	220, 260, 300	willow, rapeseed straw, wheat straw
[85]	2018	- densification of torrefied refuse-derived fuel	260	municipal solid waste
[86]	2018	- correlations to predict elemental compositions and heating value of torrefied biomass	200–300	birch, spruce, willow, beech wood, lauan, wood mixture, black locust, pine, eucalyptus, poplar, leucaena, sawdust, cedar wood, ash, aspen

Table A1. Cont.

Ref.	Year	Application	Process Temp. (°C)	Material
[87]	2018	- torrefaction of manually pressed and liquid nitrogen treated of microalgae for bioenergy utilisation	200, 300	microalgae
[88]	2018	- production upgraded wood fuel by torrefaction	200–300	raw Japanese cedar chips
[89]	2018	- properties of product biomass torrefaction based on three major components: hemicellulose, cellulose, lignin	210, 240, 270, 300	microcrystalline cellulose, beechwood xylan (representative of hemicellulose), alkali lignin
[90]	2018	- properties of torrefied waste blends	300	paper fiber, plastic waste
[91]	2018	- investigate the optimal temperature range for waste Wood and the effect torrefaction residence time had on torrefied biomass feedstock	200–400	wood waste
[92]	2018	- analyses of torrefied biomass of tropical plantation species	200, 225, 250	cupressus lusitanica, dipteryx panamensis, gmelina arborea, tectona grandis and vochysia ferruginea
[93]	2018	- concept an installation for sustainable thermal utilization of sewage sludge	300	sewage sludge
[94]	2018	- the impact of residence time, temperature, and particle size on torrefied rice husk, using a bench-scale batch reactor	240–295	rice husk
[95]	2018	- the effect of different parameters were investigated on two abundant sources of biomass in South Africa	200–300	marula seeds, blue gum wood
[96]	2018	- Solid fuel characterization of torrefied coconut shells in an oxidative environment	250–300	Local coconut Shell chips
[97]	2018	- effects of torrefaction on fuel properties of solid and condensate products	200–300	Cogon grass
[98]	2017	- comparative study on the thermal behavior of raw and torrefied bark, stem wood, stump of Norway spruce.	225, 275, 300	Norway spruce (stem wood, bark, stump)
[99]	2017	- physical and compression properties of pellets manufactured with the torrefied biomass of woody tropical species	200, 225, 250	cupressus lusitanica, dipteryx panamensis, gmelina arborea, tectona grandis, vochysia ferruginea
[100]	2017	- Preliminary production test of torrefied woody biomass fuel in a small scale plant.	215	Japanese cedar
[101]	2017	- production of torrefied solid biofuel from pulp industry waste	260, 280, 300, 320	wood waste with pulp sludge
[102]	2017	- fuel properties of torrefied sorghum biomass	250, 275, 300	sorghum, sweet sorghum bagasse
[103]	2017	- energy densification of animal waste, corn cob and pine wood	200, 250, 300	Cow dung, corn cob, pine wood
[104]	2016	- production of solid fuel from torrefied coconut leaves	245–295	coconut leaves
[105]	2016	- comparing grindability of different torrefied biomass pellets in different laboratory mills	260, 308	forest residues, willow, pine, poplar, spruce, beech, straw
[106]	2016	- compositional study of torrefied wood and herbaceous materials by chemical analysis and thermoanalytical methods	200, 225, 250, 270, 300	black locust wood, wheat and rape straw
[107]	2016	- thermal desorption of wood railroad ties	250, 275, 300, 325, 350	creosote-treated wood
[108]	2016	- detailed mapping of the mass and energy balance of a continuous biomass torrefaction plant	250–265	spruce, ash, willow
[109]	2016	- thermochemical and structural changes in Jatropha curcas seed cake during torrefaction for its use as coal co-firing feedstock	200–300	jatropha curcas
[110]	2016	- biochemical conversion of torrefied norway spruce after pretreatment with acid or ionic liquid	260–310	Norway spruce

Table A1. Cont.

Ref.	Year	Application	Process Temp. (°C)	Material
[111]	2015	- identification and quantification of the condensable species released during torrefaction of lignocellulosic biomass	250, 280, 300	pine, ash wood, miscanthus, wheat straw
[112]	2015	- evaluation of solvent for pressurized liquid extraction in torrefied woody biomass	270, 300	eucalyptus wood chips
[113]	2015	- study on dry torrefaction of beech wood and miscanthus	240, 260, 280, 300	beech wood, miscanthus (sinensis)
[114]	2015	- composition, utilization and economic assessment of torrefaction condensates	200–300	spruce, bamboo
[115]	2015	- analysis on storage off-gas emissions from woody, herbaceous and torrefied biomass	250	Switchgrass (<i>Panicum virgatum</i>)
[116]	2015	- qualitative and kinetic analysis of torrefaction of lignocellulosic biomass	200, 275, 300	miscanthus, wheat straw
[117]	2015	- comparison of chemical composition and energy Property of Torrefied switchgrass and corn stover	180–270	switchgrass, corn stover
[118]	2014	- the effects of torrefaction on the basic characteristics of corn stalks	150–400	corn stalks
[119]	2014	- decomposition kinetics of torrefaction of some nigerian lignocellulosic biomass	240, 270, 300	albizia pedicellaris, tectona grandis, terminalia ivorensis, sorghum bicolor glume, sorghum bicolor stalk
[120]	2014	- process simulation of co-firing torrefied biomass in a 220 Mwe coal-fired power plant	200, 250, 270, 300	palm kernel shell
[121]	2014	- process evaluation for torrefaction of empty fruit bunch from palm oil mill	300	empty fruit bunch (EFB) from Malaysian palm oil mill
[122]	2014	- investigates the product yields and the solid product characteristics from corncob waste torrefaction	250, 300	corncob waste
[123]	2013	- analysis of efficiency simultaneous torrefaction and grinding of biomass.	240–330	Danish wheat straw, Danish spruce chips, Spanish pine chips
[124]	2013	- the influence of the chemical properties (lignocellulose composition and alkali content) on the torrefaction behavior with respect to mass loss and grindability	270, 300	Danish wheat straw, miscanthus, spruce wood chips, beech wood chips, pine wood chips, spruce bark
[125]	2013	- thermal decomposition kinetics of woods	200, 225, 250, 275, 300	Norwegian spruce, birch wood
[126]	2013	- comparison of energy properties torrefaction by microwave and conventional slow pyrolysis	200, 230, 250, 300, 350	willow
[127]	2013	- kinetic behavior of torrefied biomass in oxidative environment	225, 275	birch, spruce
[128]	2012	- chemical compositional changes during torrefaction miscanthus and white oak sawdust	220–350	miscanthus, white oak
[129]	2012	- impact biomass torrefaction under different oxygen concentration on composition of the solid by-product	240, 280	eucalyptus grandis
[130]	2012	- the effects of particle size, different corn stover components, and gas residence time on torrefaction of corn stover	250, 280	corn stover (<i>Zea mays</i>)
[131]	2012	- effect of torrefaction on water vapor adsorption properties and resistance to microbial degradation of corn stover	200, 250, 300	corn stover

Table A2. Hydrothermal carbonization (HTC)—detailed thematic analysis.

Ref.	Year	Application	Process Temp. (°C)	Material
[132]	2019	- improvement of corn stover fuel properties via hydrothermal carbonization	120–280	corn stover
[39]	2018	- hydrothermal carbonization of peat moss and herbaceous biomass (miscanthus)	240	peat moss; miscanthus
[133]	2018	- hydrothermal carbonization of biosolids from waste water treatment plant	180, 200, 220	sewage sludge
[134]	2018	- hydrothermal carbonization of fruit wastes	190, 225, 260	rotten apple, apple chip pomace, apple juice pomace, grape pomace
[135]	2018	- the impact of hydrothermal carbonisation on the char reactivity of biomass	200, 225	wood, olive cake
[136]	2018	- impact feedstock, reaction conditions and post-treatment on properties of hydrochar	180, 220, 250	wheat straw, beech wood
[137]	2017	- evaluation of hydrochars from lignin hydrous pyrolysis to produce biocokes after carbonization	250, 300, 330–500	the pine kraft lignin
[138]	2017	- hydrothermal carbonization of loblolly pine using a continuous, reactive twin-screw extruder	200, 215, 235, 255, 260, 275, 290, 295	loblolly pine, slash pine
[139]	2017	- process design, modeling, energy efficiency and cost analysis hydrothermal carbonization of waste biomass	180, 220, 250	off-specification compost, grape marc
[140]	2014	- effects of wet torrefaction on reactivity and kinetics of wood under air combustion conditions	175, 200, 225	Norway spruce, birch

Table A3. The use of torrefied biomass in the pyrolysis process—detailed thematic analysis.

Ref.	Year	Application	Process Temp. (°C)	Material
[141]	2019	- effects of pyrolysis temperature and retention time on fuel characteristics of food waste feedstuff and compost for co-firing in coal power plants	300–500	food waste, compost, feed
[142]	2019	- combined organic acid leaching and torrefaction as pine wood pretreatment before fast pyrolysis	530	pine wood
[143]	2018	- expedient prediction of the fuel properties of carbonized woody biomass based on hue angle	300–410	rubber tree, softwood bark, softwood lumber waste
[144]	2018	- energy and exergy analyses of sewage sludge thermochemical treatment	250, 275, 480, 530	sewage sludge
[145]	2018	- impact of thermal pretreatment temperatures on woody biomass chemical composition, physical properties and microstructure	220, 260, 300, 350, 450, 550	cherry wood
[146]	2017	- compared fast pyrolysis experiments of raw and torrefied woody biomass feedstocks.	250–300, 500	ash, spruce, mixed waste wood
[147]	2017	- staged thermal fractionation for segregation of lignin and cellulose pyrolysis products	250, 275, 300–400, 500–600	red oak
[148]	2017	- thermal decomposition kinetics of wood and bark and their torrefied products	225–450	Norway spruce
[149]	2017	- combined heat and power from the intermediate pyrolysis of biomass materials	450–550	wood feedstock—pine sawdust or ground pine chips
[150]	2017	- evolution of chars during slow pyrolysis of citrus waste	200–650	citrus waste
[151]	2016	- the effect of torrefaction temperature and time on pyrolysis of centimeter-scale pine wood particles	225, 250, 275, 300, 520	pine wood cuboid
[152]	2016	- mild hydrothermal conditioning prior to torrefaction and slow pyrolysis of low-value biomass	300, 600	willow, rye grass
[153]	2016	- thermal desorption of creosote remaining in used railroad ties	200, 250, 280, 300, 450	red oak, quercus rubra

Table A3. Cont.

Ref.	Year	Application	Process Temp. (°C)	Material
[154]	2016	- Effect of torrefaction temperature on lignin macromolecule and product distribution from catalytic pyrolysis	500	The southern pine, switchgrass
[155]	2015	- unified kinetic model for torrefaction-pyrolysis	260, 280, 300, 315, 330, 375, 400, 425	aspen wood
[156]	2015	- production and characterization of bio-oil and biochar from the pyrolysis of residual bacterial biomass from a polyhydroxyalkanoate production process	550	residual bacterial biomass
[157]	2014	- characterization of biochar from switchgrass carbonization	300, 350, 400	switchgrass
[158]	2013	- a comparison of producer gas, biochar, and activated carbon from two distributed scale thermochemical conversion systems used to process forest biomass	350–750	lumber, debarked logs, bark, foliage, douglas-fir, lodgepole pine
[159]	2009	- kinetic study on thermal decomposition of woods in oxidative environment	220–590	aspens, birch, oak, pine

Table A4. The use of torrefied biomass in the gasification and co-combustion process—detailed thematic analysis.

Ref.	Year	Application	Process Temp. (°C)	Material
[160]	2019	- combustion improvements of upgraded biomass by washing and torrefaction	1400–1600	road side grass, miscanthus, wheat straw, spruce bark
[161]	2019	- thermal analysis of olive tree pruning and the by-products obtained by its gasification and pyrolysis	550, 900	olive tree pruning
[162]	2019	- theoretical and experimental analysis on co-gasification of sewage sludge with energetic crops	950	sewage sludge, virginia mallow
[163]	2019	- torrefaction as a valorization method used prior to the gasification of sewage sludge	350–900	sewage sludge
[164]	2019	- Influence of microwave pre-treated Palm Kernel Shell and Mukah Balingian coal on co-gasification	50.2–470.4	palm kernel shell
[165]	2018	- high temperature gasification of high heating-rate chars using a flat-flame reactor.	1300	Norway spruce
[166]	2018	- analyzed the possibility of co-firing a series of avocado biomass samples carbonized with coal.	400, 500, 600	avocado pit
[167]	2018	- torrefaction of healthy and beetle kill pine and co-combustion with sub-bituminous coal	500	healthy pine, beetle kill pine
[168]	2018	- coupled effect of torrefaction and blending on chemical and energy properties for combustion	900	napiers grass, rice straw, cassava stalks, corn cob
[169]	2018	- co-gasification of pine and oak biochar with sub-bituminous coal in carbon dioxide	833, 900, 975	pine biochar, oak biochar, coal, pine biochar-coal blend, oak biochar-coal blend
[170]	2017	- effect of torrefaction on the process performance of gasification of hardwood and softwood	850	spruce, ash
[171]	2017	- CFB gasification of commercial torrefied wood pellets	800–850	wood,
[172]	2017	- Organic carbon emissions from the co-firing of coal and Wood in a fixe Bed combustor	400	pine wood, pine sawdust
[173]	2017	- optimization of a bubbling fluidized bed plant for low-temperature gasification of biomass	900	pine, chestnut, shell, olive stone, grape, olive pomaces, cocoa shell
[174]	2017	- The effect of torrefaction on syngas quality metrics from fluidized bed gasification of SRC willow	900	willow
[175]	2016	- characterization and the effect of lignocellulosic biomass value addition on gasification efficiency	900	sugarcane bagasse

Table A4. Cont.

Ref.	Year	Application	Process Temp. (°C)	Material
[176]	2016	- torrefied pine as a gasification fuel using a bubbling fluidized bed gasifier	790, 935, 1000	pine
[177]	2015	- the combustion characteristics of high-heating-rate chars from untreated and torrefied biomass fuels	1100	willow, eucalyptus
[178]	2015	- characterizes the oxidation properties biomass char and compare with that of raw biomass char	900, 1200	palm kernel shell
[179]	2015	- design, optimization and energetic efficiency of producing hydrogen-rich gas from biomass steam gasification	700	oil palm
[180]	2014	- gasification of torrefied wood: a kinetic study	750	birch, spruce
[181]	2014	- lab-scale co-firing of virgin and torrefied bamboo as a fuel substitute in coal fired power plants	1400–1600	bamboo species guadua angustifolia kunth, willow
[182]	2014	- gasification of torrefied Miscanthus x giganteus in an air-blown bubbling fluidized bed gasifier	600, 700, 750, 800, 850	miscanthus x giganteus
[183]	2014	- high-temperature rapid devolatilization of biomasses with varying degrees of torrefaction	500, 700, 900, 1200	palm kernel shell
[184]	2013	- flame characteristics of pulverized torrefied-biomass combusted with high-temperature air	1150	palm kernel shells

Table A5. Other issues regarding the use of torrefied biomass—detailed thematic analysis.

Ref.	Year	Application
[185]	2019	- Boosting carbon efficiency of the biomass to liquid process with hydrogen from power
[186]	2019	- Influence of structural modification on VOC emission kinetics from stored carbonized refuse-derived fuel
[187]	2019	- Process simulation of an integrated biomass torrefaction and pelletization (iBTP)
[188]	2019	- Evaluating integration of biomass gasification process with solid oxide fuel cell and torrefaction process
[189]	2018	- Improving carbon efficiency and profitability of the biomass to liquid process with hydrogen from renewable power
[190]	2018	- Integrated systems analysis of electricity, heat, road transport, aviation, and chemicals: a case study for the Netherlands
[191]	2018	- International vs. domestic bioenergy supply chains for co-firing plants: The role of pre-treatment technologies
[192]	2018	- Use of biomass in integrated steelmaking—Status quo, future needs and comparison to other low-CO ₂ steel production technologies
[193]	2018	- climate impact and energy efficiency of internationally traded non-torrefied and torrefied wood pellets from logging residues
[194]	2018	- Coupling of an acoustic emissions system to a laboratory torrefaction reactor
[195]	2017	- Technical assessment of the Biomass Integrated Gasification/Gas Turbine Combined Cycle incorporation in the sugarcane industry
[196]	2017	- An LCA-based evaluation of biomass to transportation fuel production and utilization pathways in a large port's context
[197]	2017	- The role of bioenergy and biochemicals in CO ₂ mitigation through the energy system—a scenario analysis for the Netherlands
[198]	2017	- a whole-systems analysis of the value chain associated with cultivation, harvesting, transport and conversion in dedicated biomass power stations
[199]	2017	- Economic impact of combined torrefaction and pelletization processes on forestry biomass supply
[200]	2017	- thermoliquefaction of palm oil fiber using supercritical ethanol.
[201]	2017	- The climate contribution of biomass co-combustion in a coal-fired power plant
[202]	2017	- the influence of pre-treatment of biomass on products distribution and characteristics of torrefaction products
[203]	2016	- Influence of mill type on densified biomass comminution.
[204]	2016	- Techno-economic and carbon emissions analysis of biomass torrefaction downstream in international bioenergy supply chains for co-firing
[205]	2016	- An energy analysis comparing biomass torrefaction in depots to wind with natural gas combustion for electricity generation

Table A5. Cont.

Ref.	Year	Application
[206]	2016	- Processing and sorting forest residues: Cost, productivity and managerial impacts
[207]	2016	- Fast hydrothermal liquefaction for production of chemicals and biofuels from wet biomass—The need to develop a plug-flow reactor
[208]	2016	- Technical improvements and economic-environmental assessment along the overall torrefaction supply chain through the SECTOR project
[209]	2016	- an assessment of the torrefaction of north american pine and life cycle greenhouse gas emission
[210]	2016	- Optimal production scheduling for energy efficiency improvement in biofuel feedstock preprocessing considering work-in-process particle separation
[211]	2016	- optimization the minimum production cost for the production of woody biofuels
[212]	2016	- Prediction of high-temperature rapid combustion behaviour of woody biomass particles
[213]	2016	- Environmental and Energy Performance of the Biomass to Synthetic Natural Gas Supply Chain
[214]	2016	- Modeling of biofuel pellets torrefaction in a realistic geometry
[215]	2015	- regionalized techno-economic assessment and policy analysis for biomass molded fuel in China
[216]	2015	- Investigation into the applicability of Bond Work Index (BWI) and Hardgrove Grindability Index (HGI) tests for several biomasses compared to Colombian La Loma coal
[217]	2015	- Explosion characteristics of pulverised torrefied and raw Norway spruce (<i>Picea abies</i>) and Southern pine (<i>Pinus palustris</i>) in comparison to bituminous coal
[218]	2015	- high moisture corn stover pelleting in a flat die pellet mill fitted—physical properties and specific energy consumption
[219]	2015	- comparative cradle-to-gate life cycle assessment of wood pellet production with torrefaction
[220]	2011	- to achieve a first understanding of the possibility to combine torrefaction and hydrolysis for lignocellulosic bioethanol processes, and to evaluate it in terms of sugar and ethanol yields

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