energies

Review

The Gasification of Marine and Coastal Resources for Syngas Production: A Review

Gwendal Vonk [1], Virginie Boy [2], Jean-Louis Lanoisellé [1,†] and Thomas Lendormi [1,*]

[1] Univ. Bretagne Sud, UMR CNRS 6027, IRDL, F-56100 Lorient, France; gwendal.vonk@univ-ubs.fr
[2] Univ. Bretagne Sud, UMR CNRS 6027, IRDL, F-56300 Pontivy, France; virginie.boy@univ-ubs.fr
* Correspondence: thomas.lendormi@univ-ubs.fr
† Deceased author.

Abstract: Coasts are home to one-third of the human population. In the process of energy transition, local biomass and waste resources represent a renewable fuel that can substitute fossil fuels in order to reduce greenhouse gas emissions, hence including marine resources as part of the eligible feedstock for renewable energy production. Gasification regroups different technologies that aim to convert a solid fuel into a useful gas, and has several applications, such as heat production, power generation, and chemical synthesis. Gasification technologies regroup the traditional "dry" processes that use relatively dry fuels, but recent developments have been made with "wet" processes such as hydrothermal gasification, in sub- or supercritical conditions for the water, which can accept wet fuel. This review focuses on scientific articles that performed gasification of marine resources in order to produce a syngas. First, a definition of marine resources is made, followed by the presentation of marine resources studied in the literature. Secondly, this review presents the different types of gasification reactors and their operating conditions, followed by a summary of the different syngas produced with their composition as a performance indicator. Finally, this review exposes the limitations of the current literature and concludes with perspective propositions.

Keywords: marine resource; gasification; syngas; algae; driftwood; plastic waste

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1. Introduction

1.1. Shores: High Density People Areas

Coasts are home to approximately a third of the global population [1,2], with around 1 billion people living within 10 km of the coastline, and up to 2.75 billion people living within 100 km from the coast [2]. The coastal population could increase up to 5.2 billion people by the 2080s, depending on assumptions about migrations [3].

The definition of "Coast" is given in the Intergovernmental Panel for Climate Change (IPCC) reports as follows: "The land near to the sea. The term 'coastal' can refer to that land (e.g., as in 'coastal communities'), or to that part of the marine environment that is strongly influenced by land-based processes. Thus, coastal seas are generally shallow and near-shore. The landward and seaward limits of the coastal zone are not consistently defined, neither scientifically nor legally. Thus, coastal waters can either be considered as equivalent to territorial waters (extending 12 nautical miles/22.2 km from mean low water), or to the full Exclusive Economic Zone, or to shelf seas, with less than 200 m water depth" [4]. This definition regroups land and water areas under a unique term, and as a synthesis for this paper we take "coastal" as the area composed of the sea area with a maximum width of 22.2 km, and the land area with a 100 km width.

Coastal areas represent a large part, if not all, of numerous countries such as in the Caribbean, Central America, Chile, North, West and South Europe, South East Asia, and of course island states.

1.2. Energy Consumption

In 2022, energy consumption resumed its growing trend from before the COVID-19 epidemic by reaching a new record of 594 EJ (or 165 PWh/y), still mainly based on fossil fuels (32% oil, 24% natural gas, 28% coal, 4% nuclear + hydro, and 12% renewables) [5]. These fossil fuels are extracted from concentrated spots and then are transported to be distributed to every country. This transportation involves the use of boats, which implies crossing coastlines of countries.

On a global scale, energy consumption has only risen for the last two centuries. Energy consumption initially only relied on "traditional biomass". Then, the energy consumption increase has been sustained first by the use of coal, which was then seconded by oil, and then with the addition of natural gas, and finally with the other sources of energy, hydropower, nuclear, and so-called "renewable energy" (solar, wind, biofuels, …), as shown in Figure 1. As a consequence, humankind never performed an energy transition, which by definition is the replacement of a source by another. Humankind only performed energy addition, by always consuming more.

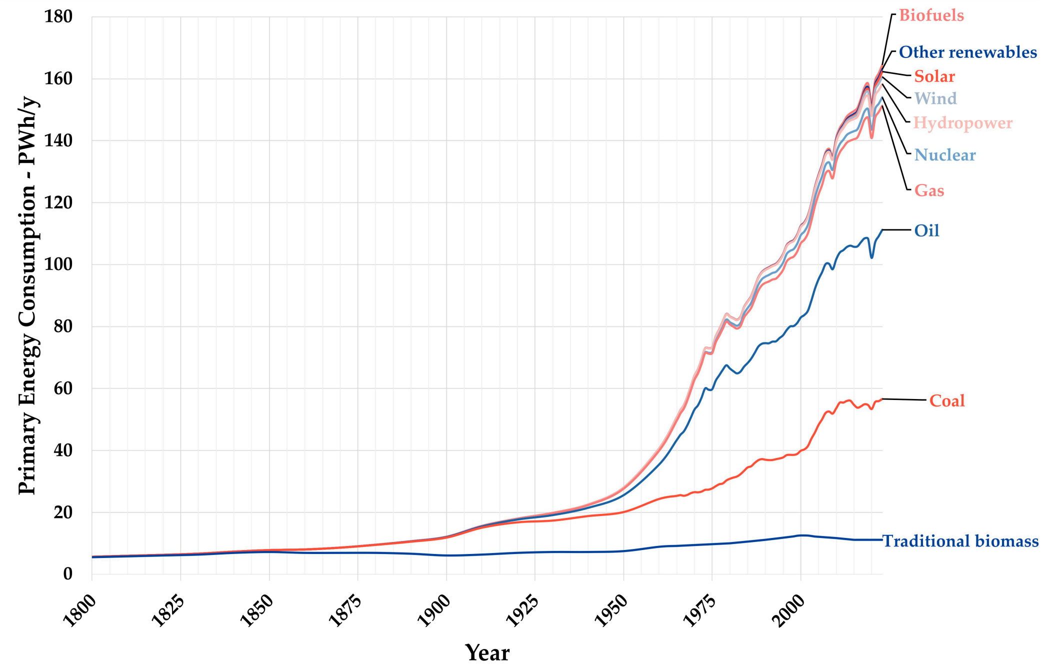

Figure 1. Global primary energy consumption by source (in PWh/y—P: Peta) since 1800—data from [6].

Today, energy consumption relies on fossil fuels of up to 84%. Fossil fuels release CO_2 in the atmosphere today at concentrations never seen since at least 800,000 years ago [7], as well as releasing other harmful substances (heavy metals, ashes, fine particles, …) in the environment. A 100% biobased energy system has already been possible in human history, namely before 1850, as shown in Figure 1. This was possible almost entirely by the use of traditional biomass. However, one must be careful to develop the sustainable use of biomass resources to ensure renewable energy production via biomass. A dedicated focus on the development of the energy valorization of biomass has to be made to ensure the serious energy transition towards a renewable and sustainable world. Nonetheless, careful development has to be made, as biomass cannot be considered as a resource like fossil fuels, and the important roles of ecosystems and biodiversity in the habitable regions of the world have to be taken into account

1.3. Energy Transition

Energy systems of countries strongly depend on fossil fuel supply, to a point where an abrupt variation in oil prices heavily affects countries which supply and consume. On one hand if fossil fuel prices are low, exporting countries faces social difficulties when national incomes mainly depend on fuel export; on the other hand, if fuel prices are high, importing countries have to reduce the quantity imported, which impacts their energy system resulting in power outages.

Fossil fuel-dependent countries are aware of this situation and know that fossil fuel supply chain disruption can occur, whether from high prices or technical issues, for example, with the Republic of Fiji. As explained in Fiji's National Energy Policy for 2023–2030 [8], energy resilience and security are their prime concerns. Fiji's government highlighted a list of threats to energy security such as climate change, disasters, oil price volatility, and the dependency on fuel imports [8]. Particularly, health and sanitary security are directly linked to energy consumption, since water supply for a large part of Fiji's population is performed via pumps using on-grid electricity and/or diesel generators [8].

1.4. Development of Biomass as a Renewable Energy Source

Biomass, as shown in Figure 1, has always had a major role in energy consumption all over the world, starting from an almost 100% energy mix based on biomass up to 1850, and decreasing today to about 6% of the primary energy consumption, tying for first place of renewable energy with hydropower. Moreover, contrary to fossil fuels and hydropower, biomass is present almost everywhere where humankind settled, even in remote areas such as islands and mountains [9].

In addition, in order to reduce greenhouse gas (GHG) emissions, bioenergy has a significant mitigation potential, assuming resources are sustainably and efficiently used [9]. The use of perennial crops and biomass residues and wastes is able to reach 80 to 90% emission reduction compared to fossil fuels, according to the Intergovernmental Panel on Climate Change (IPCC) [9].

As biomass is almost only available in low density form, it implies the need for storage, handling, preparation (drying, cutting, grinding), and transportation, which result in high costs [9,10]. It is more relevant to valorize biomass locally to minimize the resulting energy costs.

1.5. Gasification in Short: History, Process, Reactors, and Prospectives

Gasification was discovered in the XVIIth century, as reported in 1848 by M.D. Magnier in his "Handbook for engineers, directors and supervisors of gasworks" [11]. Magnier [11] reports that James Clayton sent a letter to Robert Boyle to report that he obtained, by the distillation of Newcastle Coal, three products: dark oil, aqueous fluid, and inflammable gas. Clayton said he stored the gas in a bladder to be able to burn this gas later, when he wanted to. This undated letter, written before Boyle's death in 1691, was recorded in the "British Museum" in 1848 [11]. Many others have then pursued the study and development of gasification. Magnier also reports that defining precisely the origins of gasification is complicated, especially since every country has claimed the discovery for one of its citizens: Lebon for France, Murdoch for England, Winsor for Germany, … [11]. Gasification was originally developed to produced manufactured gas, used in streetlighting, and later on for mains gas in relatively big cities or for industrial processes [11–14].

Gasification played an important role in the past in energetically constrained contexts, for example, to convert gasoline vehicles into syngas vehicles in Europe during World War II, to produce synthetic fuel via the Fischer–Tropsch process in Germany during World War II, or in South Africa during the Apartheid.

It therefore seems highly likely that gasification represents a relevant technical solution for any upcoming fossil fuel depletion situation, whether chosen or suffered.

Gasification is a thermochemical conversion technology that aims to transform a solid carbonaceous fuel into a gaseous fuel as its major product. As with any thermochemical conversion process (combustion, pyrolysis), gasification converts the solid fuel into products in three phases: solid (char and ash), liquid (water and tars), and gas. The produced gas is called synthetic gas or syngas [12]. In conventional gasification processes [12,14], the syngas is composed of hydrogen (9 to 20% *v*/*v*), carbon monoxide (10–30% *v*/*v*), methane (1–5% *v*/*v*), carbon dioxide (9–15% *v*/*v*), and nitrogen (~50% *v*/*v*), when using air.

The two main reactions in gasification are endothermic, which implies a necessary heat input in the process. Gasification processes are divided into two groups regarding heat input [10]:

1. Autothermal: The heat is produced in the gasification reactor via a partial oxidation of the fuel, usually using as air as the oxidant, but also oxygen-enriched air or pure oxygen. Using air implies the presence of nitrogen in the syngas, which reduces its heating value and the concentration of "valuable" compounds such as hydrogen. However, this configuration is the easiest and historical way to operate, since it uses the gasified fuel and only one reactor.
2. Allothermal: Heat is produced in a separate reactor and supplied to the gasification reactor. This configuration allows the use of other oxidants such as steam or CO_2, which only react in endothermic reactions. This leads to a syngas without nitrogen as the inert gas, resulting in higher concentrations of valuable compounds, and therefore, in a higher heating value of the syngas. However, this requires an additional energy source, which could lower the overall energy balance of the gasification process.

One of the drawbacks of gasification is the high impact of feedstock characteristics on the gasification behavior (bridging, tar formation, clogging) and the syngas composition [10,12,14,15], which therefore requires particular attention to the fuel pretreatment steps: drying, grinding, and sieving. In addition, operating a gasifier requires periodic control, the addition of fuel, and the removal of ashes, which result in a more labor-intensive process compared to fossil fuel processes. Another factor is the removal of pollutants (tar, hydrogen cyanide, ammonia) from the syngas, which requires additional equipment reducing economic viability and could create a local source of pollution if it is not well handled. The interest in gasification has known highs and lows, with a currently growing trend since the 2010s [16] and the development of bioenergy in an energy transition dynamic. Gasification of coal represents 20% of the world hydrogen production in 2024 [17]. Gasification units are present on each continent with hundreds of operating units ranging from small scale (10 kW) to large scale (100 MW) [18]. In the end, the perception of gasification as a "non-mature" technology is to be confronted with the actual historical and current uses at different scales of gasification, confirming gasification as an available technology for the transition towards bioenergy.

There are different gasification processes, which can be decomposed into two main routes: dry and wet [12,19].

- The dry gasification process has a low-moisture fuel and gas atmosphere around the fuel particles in the reactors. It can also be separated into two categories [12,14,19,20]:

  - Fixed bed: The fuel creates a bed which is relatively fixed (moves very slowly) compared to the air going in the reactor and the syngas going out. This implies that suitable fuels for the fixed bed must be able to produce a solid residue (char), creating the bed. In addition, this leads to high requirements for the fuel such as low ash content, high ash melting point, low moisture, … The temperature in such reactors shows a variation along the reactor height, with a peak temperature up to 1300–1400 °C in the partial oxidation area. Fixed-bed reactors cover a wide range of sizes from kW to 5 MW. This category can be decomposed into two types:
    - Downdraft**:** Fuel and air are flowing in the same direction in the reactor. This configuration produces syngas with the lowest tar content (<0.1 g/Nm^3) among all gasification technologies.
    - Updraft: Fuel and air are flowing in opposite directions in the reactor. This type leads to a high tar content in the syngas due to opposite directions of air and fuel.
  - Fluidized bed: The fuel is mixed with an inert material which creates a bed. Air is flowing from the bottom at such speed that it creates the fluidization of the inert bed and fuel. The main drawback is the limited operating temperature (900–950 °C) to avoid inert bed particles melting and agglomerating, changing their fluidization properties. This results in lower fuel conversion and higher tar content than downdraft fixed-bed gasifiers. However, fluidized-bed reactors are usually considered as fuel flexible, since they require sufficient grinding to obtain particles that can be fluidized in the same range as the inert bed. Due to the complexity of the fluidization, the lowest fluidized bed size is around 10 MW (for economic reasons) but can cover up to 100 MW.
- Wet gasification processes are rather new, with the main difference being that the medium in the reactor is not gaseous (air and syngas) but liquid, namely water [19,21,22]. In these processes, the reactor is filled with water and fuel at a low concentration (typically 1 to 8% *w*/*w*) [21]. The reactor is closed, meaning a discontinuous operation, and temperature and pressure are increased to typical values around 200–500 °C and 80 to 300 bar, respectively [22]. This leads to either a sub- or supercritical state for the water. With these conditions, the fuel decomposes into a solid (char), liquids (aqueous and hydrophobic phases), and gas. After a defined reaction time, the reactor is cooled and gasification products are liberated (gas) and have to be extracted from the water. Since water is the main medium, wet gasification processes seem to be a promising way to valorize wet biomass such as marine resources, sewage sludge, liquid manure, … These wet processes have not been well-developed so far, and are mainly used at the lab scale, which shows a great interest for these technologies.

Gasification is a technical solution included in the prospective scenario for an energy transition [10,23,24] and is considered as "a key technology in the energy transition" by the IEA [25]. The diversity of added-value products (power, biofuels, chemicals, heat) from gasification makes it relevant especially in the energy transition, especially for the transportation fuel and industry sectors, as highlighted by Monteiro and Ferreira [10]. Gasification is also mentioned in the IPCC 2022 report "Climate Change 2022—Mitigation of Climate Change" for hydrogen production, either using coal combined with CCS (carbon capture and storage) or with biomass [24]. The use of gasification technologies, however, has to go along with improvements in syngas quality and purification to ensure an economically viable and sustainable deployment [10].

1.6. Marine Resources as Fuels in Gasification

Wet biomass is better valorized in energy through “wet” processes such as anaerobic digestion. However, anaerobic digestion only valorizes ~20% *w*/*w* of the input as biogas [26], the rest is in the form of a liquid mixture containing solid particles (digestate). The digestate can be used as fertilizer, reducing the dependance on fossil fuel-based fertilizers.

The valorization of wet biomass in thermochemical conversion processes (pyrolysis, combustion, gasification) is normally not the primary solution, as it requires a drying step, demanding a considerable amount of energy and/or time.

However, in the case of a surplus of wet biomass, or after a valorization step in a biorefinery, it seems possible to consider the valorization through “dry” processes if the amount of biomass represents a problem [27] or a danger, e.g., the release of harmful substances such as H_2S during the degradation of seaweed on beaches, leading to injuries or even the death of animals and people [28,29]. As a consequence, although energy valorization of wet biomass is typically considered for “dry” processes such as gasification, these resources can be considered as a potential available energy stock, particularly in co-gasification operations [30,31].

Wet thermochemical conversion processes, namely sub- and supercritical water gasification, are also an option for valorizing wet biomass [21,31].

In addition, marine resources are not necessarily “wet”, and can be rather dry, or easy to dry, for example driftwood, which is similar to wood.

Finally, the term “coastal biomass resource” could include biomass resources up to 100 km inland from the shore. This regroups biomass from crops and their residues, woody biomass, waste, …

1.7. The Scientific Literature on Marine Resource Gasification

A search on the Web of Science on the topic of “gasificationANDmarine” leads to a total of 196 articles. With a research timespan from 1900 to 2024, articles with the topic “gasificationANDmarine” are only found starting from 1997, as presented with grey bars in Figure 2. Some of the articles are about LNG (gasification phenomenon on ships, reliquefaction), some about computational solvers (marine predators), and some about marine placers, which refer to mining. With the search on the topic of “gasification AND marine NOT LNG NOT predator NOT placer NOT liquefaction”, there are about 150 articles found on the Web of Science Core Collection.

This review selected a total of 37 articles considered as relevant for the topic of marine resource gasification for syngas production, with a total of 25 different articles performing gasification in the laboratory. The publication date starts from 2010, as presented with the green bars in Figure 2. Particularly, there is a general growing trend in the number of articles published per year about the topic of marine resource gasification to produce syngas.

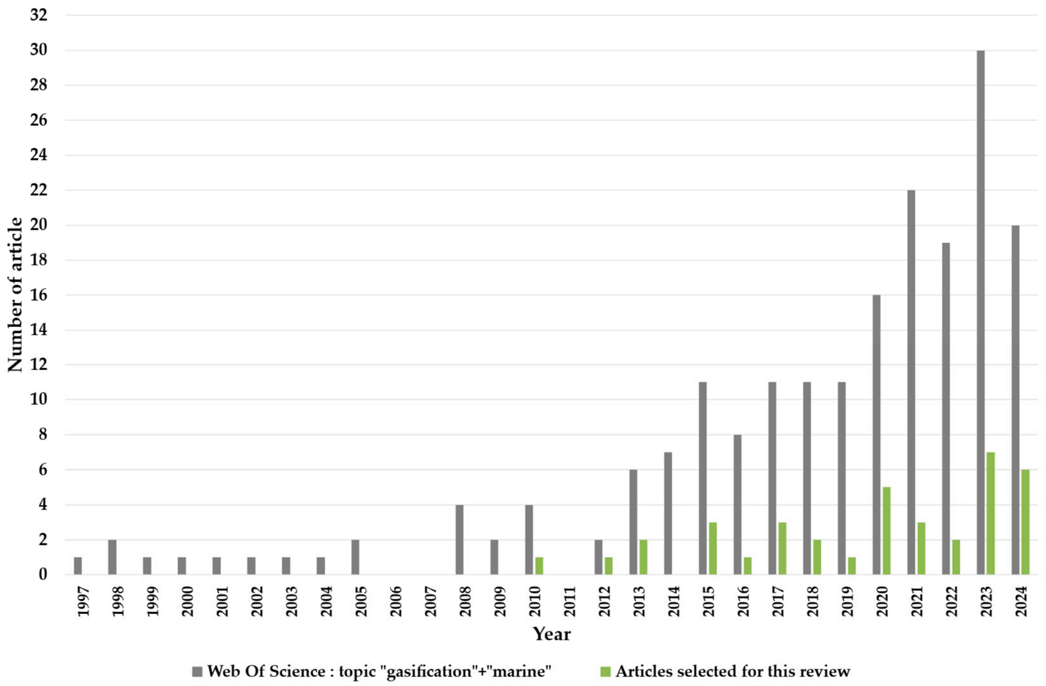

Figure 2. Yearly distribution of articles found on the Web of Science (topic "gasification AND marine") and articles selected in this review. An increasing trend is seen from the 2010s. No articles were found between 1900 and 1997.

2. Marine Resources

In this section, the different types of marine resources are presented, starting from resources from the ocean and continuing with resources from the land, since coastal areas include the land zone.

2.1. Resources from the Ocean

The term "marine" implies, firstly, the focus on resources originating from the ocean. In this sub-section, the different types of marine resources suitable or eligible for energy valorization are presented.

2.1.1. Algae

One of the main resources from the oceans to be considered as biofuel raw material is algae. With almost 300,000 species, algae are plant-like organisms but without roots, stems, and leaves [32]. Algae can be classified depending on their habitat, their chlorophyll content, or even on their metabolism. Algae are also classified, depending on their size, into two categories: microalgae and macroalgae. With the aim to be valorized into energy, this later classification is sufficient enough to characterize some fuel properties of algae.

Algae are obtained either by collecting them, on the shore as beach wrack, or by directly harnessing them from the seawater. So far, algae harvesting is not well developed, with only 0.001% of the world's available surface being exploited for algae cultivation [33]. Moreover, seaweed farming is considered as a potentially scalable ocean-based climate change solution that could provide environmental and social co-benefits [34]. Algae, as biomass, act as a natural carbon sequestration method or as a renewable bio-based resource, which could produce biofuels [34]. However, seaweed as biofuel has only been used at the pilot and experimental scale because of commercial barriers, due to the cost being too high and energy efficiency being too low [34].

In fact, depending on the gasification process considered, the fuel may have to be dried, ground, and sometimes sieved to a particular size fraction. These additional pretreatment steps are energy consuming, which reduces the energy efficiency of the overall energy valorization process.

Rowbotham et al. [35] presented a review of 37 types of macroalgae studied in pyrolysis, combustion, gasification, and hydrothermal liquefaction.

Rony et al. [33] presented a review of 27 types of algae in pyrolysis processes.

Another way to obtain algae is to collect the residues which are left on the shores by the tide. However, as wrack is composed of other materials, drifted algae are often considered as waste, with the associated handling and treatment. As waste, a reasoned management should be made according to the "Waste Hierarchy", as promoted by the European Union [36].

In a review article, Pardilhó et al. [37] conclude that drifted macroalgae exist in sufficient amounts for large scale exploitation and for various purposes such as polysaccharide extraction and biofuel production. However, due to the variability in quantities and qualities of drifted macroalgae, as well as the costs of infrastructure to collect and valorize them into materials and energy, there are still uncertainties regarding their economic and energetic viabilities.

Since drifted algae already have to be treated to avoid health and environmental issues, there is already a cost, which could be reduced, or even transformed into a gain, if material and energy are produced by drifted algae valorization.

2.1.2. Driftwood

In this sub-section, a focus is made on wood pieces sufficiently big enough to be collected without specific sorting. Therefore, the term "driftwood" refers, in the present work, to directly available wood pieces recovered from shores. The fraction of wood, called "wood debris" in this present work, that presents as mixtures of different materials will be presented in Section 2.1.4 Debris.

As presented by Murphy et al. [38], driftwood can originate from natural and anthropogenic sources and are ubiquitous in coastal waters and on shorelines. The term "wood debris" can be used, but driftwood refers to large pieces of wood or even logs that have traveled in waters, with the help of wind, waves, currents, and/or ice. Driftwood has an ecological interest as it provides materials for animal and vegetal life. Murphy et al. [38] reported in their review that driftwood has been used for millennia by Indigenous people for construction materials as well as energy sources. However, nowadays, in developed countries, driftwood represents an accumulation of foreign bodies that may disturb coastal human activities and are treated as waste.

Driftwood is present in almost all of the oceans and coasts, with a predominance in the northern Oceans due to the presence of boreal forests (North America and Asia). There is a lower driftwood concentration in southernmost latitudes due to lower human activities and the absence of trees in Antarctica. Due to specific currents and winds, driftwood mainly occurs in specific locations, in large quantities [38].

Driftwood is composed of natural sources, such as trees, branches, and bark and root systems, and anthropogenic sources, such as logs that have escaped forestry activities, vessel fragments, pieces of marine structures, planks, boards, and pallets [38].

Since driftwood has spent time in water before arriving on the shore, the specific gravity of driftwood is typically between 0.35 and 1.08 [38].

Only a few studies have considered the use of driftwood as feedstock in energetic processes [39–41].

2.1.3. Plastics

Plastics are not a natural resource from the sea and should not be considered as a marine resource. However, the increasing number of plastic particles in seawater has led to its unavoidable presence in water and on the shore, and as a result, is considered as a marine resource by this present work.

According to the International Union for Conservation of Nature in 2024 [42], 460 Mt of plastics were produced, increasing from the previous amount published in 2021 [43] of 300 Mt of plastics produced. The reported quantity of plastic debris ending up in the oceans evolved from at least 14 Mt in the 2021 report [43] up to 20 Mt in the 2024 report [42], and it has been mentioned that it will "increase significantly by 2040". Macro-plastics made up 88% of global plastic leakage to the environment in 2019 [42], which reinforces the necessity of implementing the real management of plastics, starting with the reduction in the use of plastics. Plastic particles are toxic for living beings and show, as a consequence, very low to no biodegradability.

Pham et al. [44] studied the distribution of plastic particles in the sand (surface and up to 1 m depth) of three beaches of the Azores and Canary Islands (Spain). It has been demonstrated that 84% of the total plastic particles are found below the surface and that there is an increasing plastic particle concentration towards the upper layer of the beaches.

Mallick et al. [45] studied the potential harvesting of plastic particles from the water in order to produce renewable energy with different processes. Mallick et al. [45] presented a map of oceans with the quantity of plastics in terms of mass and number of particles and reported plastic particle concentrations in the ocean ranging from 0.21 to 2219 particles/m^3.

Since plastic ends its journey in ocean water, one can also consider developing a system to valorize plastic waste into energy before it reaches the sea. This means collecting plastic waste and treating it on land, to reduce plastic in nature, and therefore avoid seawater pollution by plastic particles. This would lead to the consideration of plastic waste as a fuel resource for gasification units. This is the subject of several studies, particularly in co-gasification [46–48]. These studies will not be explored in the present work.

2.1.4. Debris

Apart from driftwood, which is sufficiently coarse to be collected specifically without pollution from other materials, the different materials found and collectable on beaches and shores are in form of a mixture, also called beach debris [49] or beach wrack [50]. This term regroups whatever can be found on the shores, usually after the tide recedes or directly after a storm. Beach wrack is made of seagrass or seaweed biomass, various marine invertebrates, as well as human-made litter, mostly plastics (since plastic particles represent 80% of all debris found in water, from the surface to deep sea sediments [43]).

Rudovica et al. [50] reported that beach wrack has an economic impact, with estimated costs between 6 and 120 € per ton of disposed wrack for the collection and removal of near-shore beach wrack, or 38 € per meter of beach and an additional 85 € per ton for material drying.

Rudovica et al. [50] studied the valorization of marine waste such as industry by-products and beach wrack into high added-value products. The samples contained a plastic residues content of up to 5% and inorganic material (ash up to 30%), described as relatively high by Rudovica et al. [50]. It is reported that elemental analysis shows a carbon content of up to 30%, with low organic chlorine and sulfur concentrations, with the HHV ranging from 8 to 15 MJ/kg [50].

Greggio et al. [49] studied the potential of fish waste and beach debris in the region of Emilia-Romagna, Italy, for energy valorization. Greggio et al. [49] reported that in the Rimini Province, beach wrack collection represents about 63,000 t/y of material, out of which 19,000 t/year are disposed of in landfills. The beach wrack was sampled and sieved for analysis, which resulted in the decomposition of the beach wrack into the following compartments:

- Recovered sand by sieving, reaching 44,100 t/y.
- About 2470 t/y of sand still remaining in the small-sized (<0.1 m) and medium-sized (0.1–0.3 m) particle fractions.
- Shells and stones representing 2290 t/y and 1490 t/y, respectively.
- The organic fraction, including driftwood in medium-sized particles and organic and driftwood in small-sized particles, reaching almost 5500 t/y.
- Anthropic litter collected during cleaning operation reaching about 870 t/y.

This analyses from Greggio et al. [49] shows the "contamination" of beach wrack by sand due to the mechanical process used to collect beach wrack. Sand is mainly made of silica, which acts as an inert material, reducing combustible properties. Moreover, in the presence of high calcium and sodium contents, silica tends to melt at lower temperatures, as seen in glass manufacturing. This could lead to the accumulation of aggregate in the reactor, and ultimately clogging, which would oblige the reactor to stop.

In summary, marine resources for fuel obviously include algae, but there are also woody types in the form of driftwood. Plastics are regrettably a marine resource and more generally, all sorts of materials mixed together in beach wrack, including sand, stones, metal, etc., are also included.

To gather or to collect these marine resources represents a cornerstone for the development of the energy valorization of marine resources.

The harvest of seaweed, as the example of marine resource harvest, has been carried out for thousands of years [51]. The harvesting techniques cover a wide range [51]:

- By hand on the shores at low tides or in shallow waters and using small cutting tools like sickles.
- Using boats to access deeper water areas and using manual rockweed cutting tools or rakes to cut, extract, and collect macroalgae.
- Highly mechanized boats with a rolling grate collecting floating algae and separating water or the so-called "suction harvester" boats, which submerge a pipe sucking the water and tearing algae off of the bottom.

Highly mechanized technologies have been intensively used in the 1980s to the 1990s, but the high harvesting performances resulted in the over-exploitation and, ultimately, the reduction in marine biomass production [51]. Several countries have banned mechanized harvesting to reduce over-harvesting and are only using boats and rakes to extract the upper part of the algae canopy, leaving some meristem algae tissue to allow regrowth [51].

2.2. Resources from the Land

Coastal areas are defined by the IPCC as the 100 km band from the coast into the land [4]. Moreover, the valorization of marine resources into energy is carried out by humans on the land. Therefore, it seems relevant to consider all the available resources from the coastal area, which include wood, crop residue, waste, and invasive species.

2.2.1. Wood, Crop Residue, and Waste

The traditional fuels in biomass gasification are wood, crop residues, and waste [15,19,20], since they are lignocellulosic biomass and create a char during thermal decomposition. The char is usually needed to form a fuel bed in the reactor, and this char is the main reactant in gasification reactions [12,14]. Marine resources, especially algae and plastics, do not have a lignocellulosic structure. Therefore, wood, crop residues, and waste could be valorized in co-gasification with marine resources in order to allow the use of traditional gasifiers. Co-gasification is a common procedure allowing the valorization of a large variety of fuels, which in a 100% composition would not be suitable in traditional gasification [46–48].

2.2.2. Invasive Species

Biomass-to-energy valorization has to include sustainability to be relevant. It may be not possible to have access to available woody biomass stocks by only cutting unexploited biomass areas, e.g., forests. As this could negatively impact biodiversity and land use, another strategy has to be deployed.

Regrettably, everywhere around the world, there are expansions of invasive biomass species, which are, by definition, a threat to local biodiversity and difficult to eradicate. There are programs that have periodically removed this invasive biomass, but waste management could represent a problem since it has to ensured that no regrowth will occur from the waste. Therefore, a thermal treatment could be a good solution to ensure the complete destruction of this invasive biomass waste.

Lately, there are several projects that have considered invasive species as a potential feedstock for biomass-to-energy valorization [52–55].

This review has selected a few land-based resources since they have been studied in gasification or co-gasification with marine resources. However, exclusive land-based resource gasification is not the aim of this review, and there are plenty of articles about the exclusive gasification of wood, crop residue, and waste [15].

3. Gasification of Marine Resources in the Current Literature

In this section, the articles in the scientific literature that have studied the gasification of marine and coastal resources in order to produce syngas are presented. First, the resources studied are presented; then, the different types of reactors used and finally, the syngas produced, and particularly the composition of the syngas, are presented.

3.1. Marine and Coastal Resources Considered as Fuel for Gasification

Among the articles selected for this review about the gasification of marine resources for syngas production, there are a total of 35 different fuels, decomposed into the following sources:

- 23 resources originated from the sea.
- 6 resources from the land (coastal area).
- 6 classified as other, particularly coal and plastic wastes.

The presence of biomass and coals in the fuels are due to the fact that the gasification tests of marine resources were performed either in comparison with “traditional” gasification fuels or in the co-gasification of a mixture of marine resources and “traditional” gasification fuels.

Marine resources from the articles selected in this review are listed in Table 1. Marine resources are mainly composed of algae (16 of the 23 marine resources), which themselves are decomposed into macroalgae (10) and microalgae (5). One article performed an Aspen

Plus simulation with an "alga" but did not precisely specify the type of alga since it was a simulation.

Table 1. Marine biomass considered as fuel for gasification in the selected literature.

Fuel/Resource	Type of Resource	Refs.
Marine Algae (Aspen Plus simulation)	Algae	[56]
Saccharina Latissima	Macroalgae	[57]
Ulva prolifera	Macroalgae	[58]
Saccharina japonica	Macroalgae	[58]
Gracilaria eucheumoides harvey	Macroalgae	[58]
Ulva Lactuca	Macroalgae	[59]
Sargassum Horneri	Macroalgae	[60]
Ulva Intestinalis	Macroalgae	[61]
Ulva Armoricana	Macroalgae	[62]
Ulva Rotundana	Macroalgae	[62]
Derbesia tenuissima	Macroalgae	[63]
Tetraselmis suecica	Microalgae	[64]
Scenedesmus almeriensis	Microalgae	[65]
Nannochloropsis sp.	Microalgae	[58,66,67]
Auxenochlorella pyrenoidosa	Microalgae	[58]
Schizochytrium limacinum	Microalgae	[58]
Spirulina Platensis (also, *Arthrospira platensis*)	Cyanobacteria	[57,58]
Driftwood	Wood collected in water	[40,68]
Rhizophora mucronata	Mangrove	[69]
Bruguiera cylindrica	Mangrove	[69]
Avicennia marina	Mangrove	[69]
Posidonia Oceanica	Plant (underwater)	[70,71]
Zostera Marina	Plant (underwater)	[58,72]

Spirulina Platensis, a cyanobacteria, has been considered in some articles, since it is nowadays a commonly cultivated marine biomass.

Lignocellulosic marine resources are also found in the literature in the form of driftwood and mangroves. Underwater plants were also studied as a gasification resource, namely *Posidonia Oceanica* and *Zostera Marina* (although considered as "seaweed" or "algae" in the literature).

Some land-based resources are included in this review since they come from articles comparing marine resource gasification performance with "traditional" resources for gasification. They are composed of crop residues (corn stalk, sugarcane bagasse), plants (Common reed), and wood (Eucalyptus, Japanese Cedar, and Japanese Cypress). However, since this review focuses on marine and coastal resources, land biomass-exclusive gasification results will not be presented.

One freshwater alga, (*Chlorella Vulgaris*), along with its waste and other resources, has been considered as a gasification fuel from the articles selected in this review. The alga *Chlorella Vulgaris* has been considered in this review because Onwudili et al. [57] studied and compared the supercritical water gasification of *Chlorella Vulgaris*, *Spirulina Platensis*, and *Saccharina Latissima*. *Chlorella Vulgaris* has been studied individually in gasification by Samiee-Zafarghandi et al. [73], Raheem et al. [74], and Valizadeh et al. [75].

Plastic waste or waste considered as marine microplastics waste has been studied in gasification [76–78], but the fuel was not collected from the ocean or beach wrack but rather was in the form new plastics.

Finally, two articles studied the co-gasification of coal and algae, one in a simulation [56] and the other one in a thermogravimetric analysis (TGA) [79].

3.2. Gasification Technologies Considered in the Literature

Different types of gasification reactors have been considered in the thermochemical conversion of marine resources. In the articles selected in this review, a total of 25 different articles have performed gasification in the laboratory, which has resulted in the number different reactors studied being 25, with the following partition:

- 13 hydrothermal gasification reactors (in sub- or supercritical conditions).
- 7 fixed-bed reactors.
- 2 thermogravimetric analysis (TGA) reactors.
- 1 free-fall tubular vertical reactor.
- 1 simulation.
- 1 fluidized-bed–spouted-bed reactor.

Considering the intrinsic difference of the reaction mediums between hydrothermal technology and the rest (fixed bed, TGA, fluidized bed), the description of the gasification technologies has been separated into two tables, namely in Table 2 for hydrothermal (or wet) technologies and Table 3 for dry technologies.

In each of these two tables, the technologies are sorted by the increasing mass of fuels studied per technology.

This variety of technologies leads to a variety of operating conditions, often making it difficult to compare between them. The operating conditions (temperature, time of reaction, pressure), when available, are reported in Tables 2 and 3.

Generally, when the value is not present in the article, "n.d." is reported, which stands for "not determined".

Hydrothermal technologies (Table 2) are also referred to as "wet" thermochemical conversion methods. These technologies are considered suitable for wet fuels, especially for biomass fuels that naturally show a high moisture percentage (from 50% *w*/*w* for fresh wood up to 90–95% *w*/*w* for sewage sludge). The presence of water, which implies an additional energy input and/or costs/time in dry thermochemical conversion processes such as gasification, is an advantage here, since organic matter is already in contact with water, the reacting medium.

Among the articles selected in this review, there are three main hydrothermal gasification technologies:

1. Subcritical water gasification, or hydrothermal gasification.
2. Supercritical water gasification.
3. Hydrothermal liquefaction followed by supercritical gasification of the obtained bio-oil + char.

Table 2. Hydrothermal-based gasification technologies studied for marine resource gasification.

Gasification Technology	**Quantity kg or kg/h**	**Time**	**Temperature—°C**	**Ref.**
Supercritical water gasification	6×10^{-5} kg	20 min	400 to 440	[61]
Supercritical water gasification, with or without NaOH and $\text{Ni-Al}_2\text{O}_3$ 36 MPa	1×10^{-3} kg	30 min	500 °C	[57]
Hydrothermal gasification 79–442 bar	1×10^{-3} kg	1 h	300 to 600 °C	[70]
Hydrothermal liquefaction then supercritical water gasification Supercritical gasification: 30–50 MPa	6×10^{-2} kg	Liquefaction 50 min heating + 60 min reaction Gasification 60 min heating + 120 min reaction	350 °C liquefaction 600 °C gasification	[58]
Supercritical water gasification in the presence of catalysts	0.7 to 5×10^{-3} kg	15 to 45 min	355 to 405 °C	[73]
Hydrothermal gasification with catalyst Ru/C	0.12×10^{-3} kg	75 min	410 °C	[67]
Supercritical hydrothermal liquefaction and gasification 350 bar	4×10^{-3} kg	60 min	200 to 500 °C	[66]
Supercritical water gasification 230 bar	0.07 to 0.4×10^{-3} kg	2 to 60 min	500 to 800 °C	[76]
Supercritical water gasification 230 bar	0.07 to 0.4×10^{-3} kg	2 to 60 min	500 to 800 °C	[78]
Sub-critical water gasification 8 MPa	5 to 25×10^{-3} kg	30 to 90 min	300 to 400 °C	[59]
Catalytic hydrothermal conversion near supercritical water conditions 200 bar	5×10^{-3} kg	60 min heating + 60 min reaction	350 °C	[80]
Hydrothermal gasification 240–250 bar	3 to 7×10^{-3} kg	7 min to 120 min stand-alone test	410–550 °C in replicated tests	[62]
Supercritical water gasification 210 to 290 bar	n.d.	2 to 60 min	500 to 800 °C	[77]

The mass of fuel involved with these "wet" gasification technologies range from 6×10^{-5} kg to 25×10^{-3} kg.

The operating conditions are pressures ranging from 0.8 to 50 MPa in parallel with temperatures ranging from 200 °C to 800 °C.

Reaction times range from 15 min to 2 h.

In order to increase selectivity in the produced syngas and/or reduce the operating parameters (pressure and/or temperature), some studies have considered the use of catalysts in the water. The reported catalysts are ruthenium over charcoal (Ru/C), sodium hydroxide (NaOH), nickel over alumina ($\text{Ni-Al}_2\text{O}_3$), manganese oxide over silica ($\text{MnO}_2/\text{SiO}_2$), and nickel oxide over silica (NiO/SiO_2).

Hydrothermal thermochemical conversion processes are rather difficult to operate since they require high pressures and relatively high temperatures. Therefore, these technologies have not reached the maturity of dry thermochemical conversion processes, resulting in rather "small"-scale reactors; hence, small amounts of fuels are able to be treated. Moreover, reactors operate in batch mode (discontinuous) and so far, no continuously operating hydrothermal reactors have been used for gasification.

Dry thermochemical conversion, grouped into fixed-bed reactor (horizontal, vertical) and fluidized-bed reactor technologies, are presented in Table 3.

Table 3. Dry gasification technologies studied for marine and coastal resource gasification.

Gasification Technology	Quantity kg or kg/h	Time	Temperature—°C	Ref.
Double fixed-bed reactor Gasifying agent: $CO_2 + H_2O$ (20%) in He	1×10^{-4} kg	80 min	400 to 700 °C (100 °C step)	[65]
Fixed-bed reactor Steam gasification: argon + steam	1×10^{-3} kg	2 h	650 to 750 °C	[72]
Tubular horizontal fixed-bed reactor	1×10^{-3} kg	20 min reaction	700 to 950 °C	[74]
Tubular horizontal fixed-bed reactor Steam gasification (50% *w*/*w* steam)	1×10^{-3} kg	10 min to 6 h	900 °C	[63]
Downdraft fixed bed—"Femto gasifier" Air blown (ventilator before reactor)	$1 \times 10^{+1}$ kg/h	137 min	600 to 900 °C on the grate	[68]
Downdraft fixed bed	$2 \times 10^{+1}$ kg/h	n.d.	n.d.	[40]
Tubular horizontal reactor Presence of catalysts (dolomite) Gasifying agent: $O_2 + H_2O$	n.d.	n.d.	850 °C	[71]
TGA	1×10^{-5} kg	80 min	900 °C	[69]
TGA	1×10^{-4} kg	135 min	700 °C	[81]
Free-fall vertical reactor Steam gasification of biochar	1×10^{-3} kg	120 min	750 to 900 °C	[60]
Aspen simulation Combined gasifier + SOFC (solid Oxide fuel cell)	3.6×10^{0} kg/h	(Equilibrium simulation)	750 °C	[56]
Fluidized bed co-gasification in spouted-bed reactor	1×10^{0} kg/h	1.5 to 4 h	850 °C	[64]

Dry thermochemical conversion is historically older and, therefore, presents with a higher maturity in industrial applications. Biomass conversion with dry processes requires the pretreatment of the biomass through drying, grinding, and sieving. Drying can be performed in a specific dryer or can be achieved naturally, as it is for wood stored outside for several months (up to 24 months) with a top cover to protect from rain.

The mass of fuel involved in these "dry" gasification technologies range from 1×10^{-5} up to 2×10^{1} kg/h.

The operating conditions are under atmospheric pressure, in parallel with temperatures ranging from 400 °C to 950 °C.

Reaction times range from 10 min to 6 h.

Gasification with dry processes is mainly performed in batch mode, but there have been three articles that have reported this process working in continuous mode (downdraft fixed bed and fluidized bed), with the highest fuel mass flow ranging from 10^{0} to 2×10^{1} kg/h.

As presented, marine resources are mainly wet; therefore, dry thermochemical conversion processes are not immediately considered to valorize these wet biomass fuels. Moreover, marine biomass seems to be restricted to algae, which do not present a lignocellulosic structure, which is one of the main requirements in fixed-bed reactors.

3.3. Syngas Composition, as Gasification Performance, in the Literature on Marine Resource Gasification

In this section, the syngas compositions produced from different fuels and reactors, with their associated operating conditions, are presented. The syngas composition is considered as the main parameter to qualify the performance of the gasification of marine resources, since the aim of gasification is to produce a syngas that will be further used in internal combustion engines or as a chemical for synthesis. First, the results from wet gasification processes are presented, followed by the syngas composition obtained with dry gasification processes.

3.3.1. Hydrothermal Processes

The composition of syngas produced from hydrothermal gasification processes is reported in Table 4, for each reactor and each fuel studied. The composition reported is either the syngas composition at optimum conditions or ranges of compositions, depending on the variation of the parameters of the study (temperature, pressure, fuel loading, …).

It should be highlighted that the main unit for syngas composition is % *v*/*v* in the table, since this is the quality of the syngas itself. However, some studies use a different set of units such as mmol/g-fuel or g/kg-fuel.

The main syngas components measured are H_2, CO, CO_2, and CH_4, and sometimes, there are values for C_xH_y (light hydrocarbons) and it is specified in the table which components are included in C_xH_y.

The column "syngas LHV/HHV" is present although few articles have reported a value.

Generally, when the value is not present in the article, "n.d." is reported, which stands for "not determined".

Table 4. Syngas composition from marine resource gasification—wet processes.

Gasification Type	**Fuel**	**H_2 % *v*/*v*-dry**	**CO % *v*/*v*-dry**	**CO_2 % *v*/*v*-dry**	**CH_4 % *v*/*v*-dry**	**C_xH_y % *v*/*v*-dry**	**Syngas LHV/HHV MJ/Nm³**	**Ref.**
Supercritical water gasification	*Ulva Intestinalis*	2 to 4 mmol/g	1.75 to 1.5 mmol/g	6 to 11 mmol/g	3.5 to 2.5 mmol/g	C_2H_6 1 to 0.5 mmol/g	n.d.	[61]
Supercritical water gasification	*Chlorella Vulgaris*	18.3	5.28	45	17.1	14.3 (C_2-C_4)	22.8	[57]
	Spirulina Platensis	21.1	4.26	36.2	21.2	16.9 (C_2-C_4)	27.9	
	Saccharina Latissima	24.8	4.23	50.2	12.0	8.74 (C_2-C_4)	17.3	
Hydrothermal gasification	*Posidonia oceanica*	300 °C: 0 600 °C: 50	300 °C: 5–8 600 °C: 0	300 °C: 95 600 °C: 25	300 °C: 0 600 °C: 25	$C_2H_6 + C_3H_8 + C_4H_{10}$ 300 °C: 0 600 °C: 0 Peak at 550 °C: 10	n.d.	[70]
Hydrothermal liquefaction then supercritical water gasification	*Nannochloropsis oceanica*	27.77	9.76	15.26	37.35	C_2H_6 9.76	n.d.	[58]
	Auxenochlorella pyrenoidosa	30.11	0.46	26.46	32.40	C_2H_6 9.89	n.d.	
	Arthrospira platensis	27.83	0.27	33.91	35.11	C_2H_6 2.69	n.d.	
	Schizochytrium limacinum	34.48	0.63	17.30	36.20	C_2H_6 11.22	n.d.	
	Ulva prolifera	28.17	0.00	28.30	35.95	C_2H_6 7.24	n.d.	
	Saccharina japonica	31.37	6.65	25.90	29.35	C_2H_6 6.06	n.d.	
	Zostera marina	33.72	0.27	33.81	26.68	C_2H_6 5.62	n.d.	
	Gracilaria eucheumoides harvey	21.05	12.40	38.35	25.73	C_2H_6 2.57	n.d.	
Supercritical water gasification with catalysts	*Chlorella* PTCC 6010	1.1–20.9	7.7–34.2	57.1–84.3	0.5–7.7	n.d.	n.d.	[73]
	Optimum: 405 °C, 45 min, 1.4% *w*/*w*	20.3	8.6	64.0	7.1	n.d.	n.d.	
Hydrothermal gasification with catalyst	*Nannochloropsis* sp.	35–40	0–5	43–50	9–18	C_2H_x 0–6	n.d.	[67]
Supercritical hydrothermal liquefaction with gasification	*Nannochloropsis* sp.	0.39 to 19.3	0.2 to 0.4 (only 450 and 500 °C)	97 to 36	0.05 to 32.6	C_2H_6 0.64 to 11.4 (300 to 500 °C)	n.d.	[66]

Supercritical water gasification of polycarbonate Parameters: 10 min/23 MPa 5% *w*/*w*/700 °C	Effect of temperature 500 to 800 °C	5–30	2–15	35–70	20–35	$C_2H_4 + C_2H_6$ 0–5	n.d.	[76]
	Effect of time 2–60 min	10–30	2–20	35–40	30–35	$C_2H_4 + C_2H_6$ 0–2	n.d.	
	Effect of feedstock concentration 5–25% *w*/*w*	17–25	5–7	30–35	35–45	$C_2H_4 + C_2H_6$ 0–1	n.d.	
Supercritical water gasification of polypropylene Parameters: 10 min/23 MPa 5% *w*/*w*/700 °C	Effect of temperature 500 to 800 °C	5–37	2–5	5–15	45–70	$C_2H_4 + C_2H_6$ 0–30	n.d.	[78]
	Effect of time 2–60 min	10–30	2–5	5–10	60–75	$C_2H_4 + C_2H_6$ 0–8	n.d.	
	Effect of feedstock concentration 5–25% *w*/*w*	12–18	1–4	2–5	75–85	$C_2H_4 + C_2H_6$ 0–1	n.d.	
Sub-critical water gasification 400 °C 90 min 8 MPa	*Ulva Lactuca* 1% *w*/*w*	8	n.d.	82	10	n.d.	n.d.	[59]
	Ulva Lactuca 5% *w*/*w*	2.5	n.d.	95	2.5	n.d.	n.d.	
Catalytic hydrothermal gasification	Marine boat wrap	26 g/kg fuel	n.d.	n.d.	n.d.	n.d.	n.d.	[80]
Hydrothermal gasification	*Ulva Armoricana* *Ulva Rotundana*	3–16	<2	40–60	3–18	n.d.	n.d.	[62]
Supercritical water gasification of polyethylene terephthalate Parameters: 10 min/23 MPa 5% *w*/*w*/700 °C	Effect of temperature 500 to 800 °C	5–25	5–25	45–55	18–22	$C_2H_4 + C_2H_6$ 0–2	n.d.	[77]
	Effect of time 2–60 min	8–20	5–20	50–55	~20	$C_2H_4 + C_2H_6$ 0–1	n.d.	

The main property of syngas produced from wet gasification processes of marine resources is the high content of CO_2, which is the main component in many cases, with a content ranging from 30% *v*/*v* to 95% *v*/*v* of the syngas. The fuel studied is mainly biomass (algae or plant), which, from elemental analyses, show a high oxygen content compared to fossil fuels. Therefore, the oxygen contained in the fuel ends up in the form of CO_2 in hydrothermal gasification.

The CO content in syngas from hydrothermal processes is low, ranging from 0 to 12% *v*/*v*. CO is the gas with the lowest concentration. The H_2 content ranges from low contents (0 to 1% *v*/*v*) at lower temperatures to high contents (20 to 40% *v*/*v*) at higher temperatures. The CH_4 content is similar to the H_2 content but lower, with the same evolution when changing operating conditions. Light hydrocarbons (C_2 to C_4) are sometimes measured and show contents from 0 to 16% *v*/*v*, following the evolution of CH_4 contents.

The use of a catalyst results in a shift in gas compositions, with increases in valuable gas components, mainly in H_2 and CH_4.

Sub-critical water conditions seem to lead to syngas with lower H_2 and CH_4 concentrations and higher CO_2 concentrations than supercritical water conditions.

There are also studies of the hydrothermal gasification of plastics, namely polycarbonate by Bai et al. [76], polyethylene terephthalate by Bai et al. [77], and polypropylene from Bai et al. [78]. As polycarbonate and polyethylene terephthalate contain oxygen, the syngas produced shows similar CO_2 contents (30 to 55% *v*/*v* [76,77]) to that of the syngas from biomass. Only the hydrothermal gasification of polypropylene [78], containing no oxygen in the elemental analysis, shows low CO_2 contents, from 2 to 15% *v*/*v*. Since there is no oxygen in the fuel, CO_2 from the hydrothermal gasification of polypropylene seems to result from reactions between H_2O and the fuel.

The severity of the treatment allows a shift in the syngas compositions. As exhibited by Brown et al. [66], when increasing the temperature from 200 to 500 °C, at 350 bar, the gas compositions show the following changes:

- An increase from 0 to 19% *v*/*v* for H_2.
- A decrease from 97 to 36% *v*/*v* for CO_2.
- An increase from 0 to 32% *v*/*v* for CH_4.

The CO content seemed to not be altered by this temperature increase.

In order to produce a higher quality syngas, hydrothermal gasification seems to have to be performed at high severity, meaning high temperature and high pressure. At such conditions, the syngas produced can show high hydrogen content [57,67,70] from 20 to 50% *v*/*v*, which can compete with the hydrogen content in the syngas from methane steam reforming, a process which nowadays accounts for 60% of the worldwide hydrogen production [17].

The available data given in the selected articles for wet gasification processes are, however, not enough to assess the performance of gasification in depth or to compare the results from one study to another. The most limiting factor for wet gasification processes is the lack of mass and energy balance, which dramatically limits the possible discussion of the process performance.

Since hydrothermal gasification, with sub- and supercritical water, requires energy input in terms of heat and pressure, it is of utmost importance to determine the required energy to sustain the syngas production and qualify the performance of any energetic process. So far, there are almost no energy balance analyses performed with the hydrothermal gasification of marine resources that can evaluate the energetic yield in syngas compared to the energetic input of the processes.

3.3.2. Dry Gasification Processes

The composition of syngas produced from dry gasification processes is reported in Table 5, for each reactor and each fuel studied. The compositions reported are either the syngas composition of the optimum conditions or ranges of compositions, depending on the variation of the parameters of the study.

It should be highlighted that the main unit for syngas composition is % *v*/*v* in the table, since this is the quality of the syngas itself. However, some studies use a different set of units such as mmol/gC, % of measured gas, g/g-sample(daf), mL/g, or % of carbon converted (daf: dry ash-free).

The main syngas components measured are H_2, CO, CO_2, and CH_4, and sometimes, there are values for C_xH_y (light hydrocarbons) and it is specified in the table which components are included in C_xH_y.

The column “syngas LHV/HHV” is present although few articles have reported a value.

It should be noted that several studies do not focus on syngas composition but rather primarily focus on the feasibility of marine resource gasification [40,56,81], the impacts of minerals in the fuel on the processes [40,63], or qualitative gas analysis [65]. Since no syngas analysis was available for these studies, we have chosen not to include them in Table 5, but still include them in this review, as they represent studies valorizing marine resources in gasification.

For the dry gasification processes reported in this review (Table 5), the syngas composition unit within the articles are all different, which makes it difficult to compare results from different articles. Only Puglia et al. [68], Conesa et al. [71], and Alghurabie et al. [64] (for co-gasification test only) used the % *v*/*v* for syngas composition.

Puglia et al. [68] performed the gasification of driftwood in a downdraft fixed gasifier in autothermal conditions and continuous mode. The syngas compositions obtained are in agreement with the literature [12,14], although in the lower range for hydrogen and in the higher range for CO_2, implying a low HHV for the syngas of 4.2 MJ/m^3 (rather, 5 to 6 MJ/m^3 in good conditions [12,14]). Since the gasifying agent is air, a large part of the syngas composition must be N_2, but it is not measured.

Conesa et al. [71] performed the gasification of *Posidonia Oceanica* in a horizontal fixed-bed reactor in an O_2/H_2O atmosphere with the presence of dolomite as the catalyst. The tests were performed in allothermal conditions in batch mode, with an unknown quantity of fuel. Considering the reactor used, the fuel mass used may be in the range of 1–100 g. The syngas compositions are in the range of compositions reported in downdraft fixed-bed gasifiers [12,14], although in the lower range for H_2 and in the higher range for CO_2 and CH_4. The temperature was set at 850 °C, lower than in downdraft fixed-bed gasifiers [12,14], which could explain the lower syngas quality due to a slower gasification reaction rate (low H_2 and high CO_2) and slower tar and hydrocarbon reaction cracking (high CH_4).

Alghurabie et al. [64] performed the gasification of coal, algae, and a mixture of coal and algae (90 and 10% *w*/*w*, respectively) in a fluidized spouted-bed reactor, with injection of air + steam, in allothermal conditions (air is preheated) and continuous mode. Tests with 100% algae could not give results due to disruptions in the process, which led to the abortion of this test. The co-gasification test with 90% *w*/*w* coal–10% *w*/*w* algae produced a syngas with lower concentrations than in the fixed bed [68,71]. Since the gasifying agent is air + steam, a large part of the syngas composition must be N_2, but it is not measured. The syngas composition from the test with 100% coal is reported in the unit "% of carbon converted into gas", except for hydrogen, which is in % *v*/*v* and ranging from 12 to 20% *v*/*v*.

Table 5. Syngas composition from marine resource gasification—dry processes.

Gasification Type	Fuel	H_2 % *v*/*v*-dry	CO % *v*/*v*-dry	CO_2 % *v*/*v*-dry	CH_4 % *v*/*v*-dry	C_xH_y % *v*/*v*-dry	Syngas LHV/HHV MJ/Nm^3	Ref.
Fixed-bed tube reactor *Composition in mmol/gC*	*Zostera Marina*	22.5	2.5	12	1	n.d.	n.d.	[72]
	Torrefied—200 °C	20	2.5	10	2	n.d.	n.d.	
	Torrefied—250 °C	18	2.5	8	2	n.d.	n.d.	
	Torrefied—300 °C	17	2	7	2	n.d.	n.d.	
Tubular horizontal fixed-bed reactor	*Chlorella Vulgaris*	20 to 30 % of measured gas	22 to 25 % of measured gas	27 to 37 % of measured gas	17 to 19 % of measured gas	n.d.	11 to 13 MJ/m^3	[74]
Downdraft fixed bed	Driftwood	11.0	17.2	12.3	1.6	n.d.	HHV: 4.2 MJ/m^3	[68]
Horizontal tube fixed bed	*Posidonia Oceanica*	8 to 15	9 to 23	12 to 21	3 to 7	C_2H_4: 1–3 C_2H_6: 0–1	n.d.	[71]
TGA	*Rhizophora mucronata*	0.03	0.32	0.30	0.06	n.d.	n.d.	[69]
	Bruguiera cylindrica	0.03	0.30	0.28	0.06	n.d.	n.d.	

Composition in g/g-sample(daf)	*Avicennia marina*	0.04	0.32	0.44	0.06	n.d.	n.d.	
	Eucalyptus	0.03	0.30	0.24	0.06	n.d.	n.d.	
	Japanese cedar	0.03	0.40	0.24	0.06	n.d.	n.d.	
	Japanese cypress	0.03	0.44	0.22	0.06	n.d.	n.d.	
Free-fall vertical reactor Steam gasification of biochar Temperature 750 °C to 900 °C *Composition in* mL/g	Corn Stalk (char)	32–52	35–25	22–20	8–2	1–0	n.d.	[60]
	Common reed (char)	38–55	32–12	30–20	10–2	1–0	n.d.	
	Sargassum Horneri (char)	40–58	42–8	10–30	12–2	<1	n.d.	
Fluidized-bed co-gasification spouted-bed reactor	100% coal (* % of carbon in the gas)	12–20	25–40 *	50–62 *	3.5–6 *	n.d.	n.d.	[64]
	100% algae	Aborted test due to abnormal compartment of the gasification						
	10% algae 90% coal	6–9	11–13	10–13	1	n.d.	n.d.	

The other articles studying the dry gasification of marine resources show the feasibility of using marine resources in gasification for syngas production. Raheem et al. [74] and Zahra et al. [72] studied the gasification of *Chlorella Vulgaris* and *Zostera Marina*, respectively. The syngas compositions show a high content of hydrogen but low CO content with the gasification of *Zostera Marina* and its torrefied derivatives [72]. The gasification of *Chlorella Vulgaris* produced a syngas with similar concentrations of H_2, CO, CO_2, and a slightly lower concentration of CH_4 [74].

Sakurai et al. [69] and Li et al. [60] compared the gasification of marine resources with "traditional" fuels such as wood [69], crop residue, and plants [60]. Syngas compositions from marine resources are similar to that of traditional fuels.

The gasification of marine resources in dry gasification processes is a possible route for syngas production despite the potentially high moisture contents of the fuels.

The available data in the articles of both wet and dry gasification processes are usually not enough to assess the performances of gasification in depth, as well as to compare results. Syngas analysis units are not the same and particularly, do not permit the evaluation of the quality of the syngas, for example, when using units in g/g-sample(daf) [69], mL/g [60] or mmol/gC [72]. The lack of mass and energy balance of dry processes dramatically limits the possible discussion of process performance. Finally, the mass studied, when below 10^{-3} kg, represents too small a quantity to be able to extrapolate data to real working units.

Either for wet or dry gasification, the higher the operating condition (namely, temperature and pressure), the higher the combustible gas contents in the syngas: H_2 and CH_4 for wet gasification and H_2 and CO for dry processes. Therefore, the utilization of the syngas could drive the choice for a particular gasification technology.

Apart from lab-scale conditions, one of the factors defining the choice for a particular gasification process will be the available commodities such as electricity and heat in the environment of the plant. Wet gasification processes need external energy sources to sustain gasification conditions, while dry gasification processes can be performed, with the proper conditions, in an autonomous way regarding energy, and even can produce electricity and heat.

In conclusion of this section, the gasification of marine and coastal resources to produce syngas appears to be technically feasible at the laboratory scale with a wide variety of reactors in different operating conditions. However, limitations regarding the results and operating conditions still have to be overcome.

4. Limitations of the Current Literature

In this section, the limitations encountered in this review of the current literature of the gasification of marine resources for syngas production are presented.

4.1. Limitations of Syngas and Mass–Energy Balance Analysis

The first limitation encountered is the lack of homogeneity in the syngas analyses reported in the literature, as exhibited in Tables 4 and 5. Gasification processes aim to produce a syngas that will be further used, and the main properties are the concentrations of each gas in the syngas, along with the flow rate. For syngas description, units involving the mass of syngas should be avoided, since syngas is a mixture of gases with wide range of molecular weights and it lowers the importance of hydrogen over CO_2. Moreover, since syngas is, by definition, in gas phase, the ideal gas law, which is relevant for the pressure range of industrial applications, implies that the volumes and concentrations are considered as the main parameters of the gas.

The gas concentrations should be presented in % *v*/*v* or equivalent units (mol/mol).

Analyses of gas yields based on fuel mass (/kg-fuel) are interesting in the analysis of the gasification process, but they may distort the perception of syngas quality. Moreover, gasification is the result of the two main reactions that convert the solid char into CO and H_2. These reactions involve CO_2 and H_2O as the reactants on solid carbon (C). In autothermal conditions, CO_2 and H_2O result from the partial oxidation of the fuel with air, which means C and H originate from the fuel, but O partially originates from the air (the other part is the O in the fuel). Therefore, expressing CO, H_2, CO_2, and CH_4 on the fuel basis means oxygen brought by the air is taken into account in the syngas but not on the fuel basis. This leads, for example, to gas yields higher than 1 kg-gas/kg-fuel for CO_2, or in other words, mass yields higher than 100% *w*/*w*, which could introduce the wrong perceptions.

This should not replace syngas analyses in % *v*/*v* but rather must be added in the mass balance analysis.

In the selected articles, very few articles performed a mass balance and energy balance of the gasification process. Producing a high-quality syngas is the main objective of gasification, but it should also produce "large" quantities of gas, since the aim is to convert the majority of solid fuel into combustible gases.

Mass balance allows the analysis of the performance of the gasification process itself and may be good to identify perturbations, if the liquid or solid phase is too high. This also helps to identify the treatment of gasification residues, such as char, ashes, fine particles (solid), and water and tar (liquid), and especially the amount of residues to deal with, which will impact the economical balance of any gasification project.

Energy balance is also of high importance, especially since gasification could be conducted in autothermal or allothermal mode.

Allothermal gasification requires an external energy input (heat, pressure) to sustain the temperature and pressure in the reactor, to preheat the air, to produce "hot" steam… These energy needs negatively impact the energy yield of the gasification process. For laboratory purposes, one should understand the need for allothermal conditions, since a self-sustaining gasification reactor can be difficult to run at small scale due to heat losses. This does not take into account the energy input, which results in distorted results regarding the performances of allothermal gasification processes.

Autothermal gasification is closer to industrial applications, and an energy balance analysis allows the assessment of the performance of the process and the identification of possibilities for improvement.

One tool used in the energy balance analysis is the EROI, or Energy Return On Investment, which allows us to precisely compare the energy input needed and the useful energy produced by a process. This allows the comparison of the different gasification processes and the identification of the more energy efficient ones.

4.2. Operating Conditions Not Representative of Real Applications

The quantities of fuel involved in the selected studies are in general relatively low, in the range of 10^{-6} to 10^{-1} kg, and only three articles studied a relatively high amount of fuel, in the range of 10^{0} to 10^{1} kg/h.

When concluding about the relevance of a process in terms of its capability to produce energy, it seems necessary to be on the same scale of the actual use of energy, or at least on the same scale as the amount of fuel available.

An internal combustion engine develops mechanical power in the order of 10 to 100 kW using thermal power of around 30 to 300 kW (33% yield at best). Considering biomass (wood with an LHV of 18 MJ/kg, as an example), this represents a consumption of around 6 to 60 kg/h to develop 30 to 300 kW thermal energy.

If the amount of fuel available is the reference, a yearly production/gathering at the scale of a city/region could reach from 1000 to 10,000 t/y (example of 60,000 t/y of driftwood in Italy, estimated by Bartocci et al. [40]). This means an uninterrupted hourly "production" of 115 to 1150 kg/h.

Hence, gasification units, and any other energy production/conversion unit, should have a capacity ranging either from 10 to 100 kW or from 10 to 1000 kg/h to be able to represent a realistic application with concrete results and usage.

4.3. Operating Conditions of the Dry Gasification: A Temperature Minimum

The two main reactions occurring in gasification, converting carbon into CO and CO + H_2, are:

$$\mathrm{C} + \mathrm{CO_2} \rightleftarrows 2\ \mathrm{CO} \tag{1}$$

$$\mathrm{C} + \mathrm{H_2O} \rightleftarrows \mathrm{CO} + \mathrm{H_2} \tag{2}$$

At atmospheric pressure, these reactions have a chemical equilibrium constant equal to 1 around 680 °C (950 K), and values above 10^4 for a temperature of at least 980 °C (1250 K) [12]. This means that at atmospheric pressure and below 680 °C, these reactions are not thermodynamically favorable. For temperatures below 680 °C, it is not possible to perform gasification but only, reactions from the pyrolysis and cracking of fuel and tars are performed.

Due to Le Chatelier's principle, an increase in pressure should displace the equilibrium to the left of the equations. Hence, an increase in pressure will not decrease the equilibrium temperature but rather increase it [12].

The higher the temperature, the more the equilibrium is displaced to the right. In addition, the chemical equilibrium constant can be defined as the ratio of the direct reaction rate (r_{direct}) over the indirect reaction rate ($r_{indirect}$):

$$K = \frac{r_{direct}}{r_{indirect}} \tag{3}$$

Hence, a high value of the chemical equilibrium constant means a higher reaction rate in the way of the production of syngas.

For maximum fuel conversion into syngas, one should aim for the biggest chemical equilibrium constants, at least above 10^4 to reach the "quasi-complete" conversion of fuel and rapid conversion.

In downdraft fixed reactors, temperatures can reach up to 1200–1500 °C in the oxidation area [14]. Since the two gasification reactions are endothermic, the temperature decreases rapidly in the char area, down to 700–750 °C, where the equilibrium is almost reached and reactions are kinetically slowed or even stopped [14,82]. It is reported that the actual gasification reactions take place over a relative short length in the char bed, with 90% of the reduction in char achieved over the first 5 to 10 cm below the oxidation zone, and up to 95% of the conversion over 20 cm [82].

4.4. Limitations of Analysis of By-Products of Gasification: Char, Tar, and Pollutants (H_2S, NH_3, and HCN)

Gasification is a process that converts a solid fuel into syngas, but there are several other compounds that are produced, which usually represent a burden as they need specific treatment and additional cost: tars, char/ashes, and syngas pollutants such as H_2S, NH_3, and HCN.

In the articles selected in this review, no focus has been made on these side products/residues. However, depending on the use of the syngas, one should remove pollutants including the following:

- Char/ashes: Solid residue containing minerals and potentially enriched in heavy metals. Often, the treatment is only landfilling, sometimes with "hazardous waste" status.
- Tars which can cause clogging of the moving pieces of engines.
- H_2S which produces toxic atmospheric pollutants (SO_2) and poison catalysts (Fischer–Tropsch).
- NH_3 which produces atmospheric pollutants (NO_x).
- HCN which produces toxic atmospheric pollutants (NO_x).

Analyses of the specific fuel considered and gasification residues/pollutants have to be developed to assess the level of pollution and risk linked with the gasification unit in order to ultimately avoid the risk of being banned by local regulations of gasification technologies as one of the solutions in the energy transition.

4.5. Supercritical Gasification: Precipitation of Inorganics Causing Clogging

Supercritical water has specific properties that are radically different to that of sub-critical water. Supercritical water is obtained at a pressure above 22.1 MPa and a temperature above 374 °C.

Under a pressure of 25 MPa, water density is 630 kg/m^3 at 350 °C (sub-critical) and decreases to 170 kg/m^3 at 400 °C (supercritical) [22]. The dielectric constant drops from 80 at ambient temperature down to 2 at 450 °C [22]. This makes water, a highly polar solvent in sub-critical conditions, a non-polar solvent in supercritical conditions. Supercritical water becomes a good solvent for non-polar organic compounds (hydrocarbon such as tars), but on the other hand, as supercritical water shows very low ion products of 10^{-23} at 25 MPa and 550 °C (while it is 10^{-14} at ambient conditions), this means that the solubility of inorganics ions, e.g., salts, is almost null in supercritical water gasifiers [22]. This could lead to the deposition of salts in the reactors, clogging of catalyst pores, … As a result, corrosion is a practical issue of supercritical water gasification due to the specific properties of supercritical water [22].

Besides the properties of water and its impact on the reactor, the conditions to reach supercritical water are relatively strong: a pressure above 22.1 MPa and a temperature above 374 °C. This means that for large-scale operations, the reactor must be able to sustain and resist these harsh conditions. Mechanically speaking, this means thick reactor walls, with strong and large screws and bolts in the system. This leads to the increased use of alloy materials for the reactor, logically, negatively impacting the cost of the unit.

5. Presentation of Perspectives for Further Studies

In this section, perspectives are presented for future studies in marine resource gasification to syngas production, in order to increase general knowledge make gasification one of the solutions available to and needed for performing the energy transition towards a renewable energy mix.

5.1. Marine Resources Are Too Wet for Dry Gasification: Ways to Improve Fuel Quality or Process Flexibility

One of the main obstacles in marine resource gasification is its inherent property: high moisture, as it comes from the ocean.

In this sub-section, three points are presented that could be developed in further research work to improve the suitability of marine resource as feedstock for syngas production via gasification.

5.1.1. Integration in a Biorefinery Process

The first aspect to reduce the negative impact of the high moisture of marine resources is to consider these resources as part of a biorefinery process [54,83,84]. Biorefinery means that, before considering producing energy, one should first think of material production, for example, in the production of lipids, carotenoids, proteins, polysaccharides, vitamins, … [83]. During the transformation processes, the resource can be pretreated, such as by grinding, washing (to remove salts), drying, etc. Once the high-value-added products are extracted, there is a residue that can then be valorized into energy. This residue, depending on the process, can have more suitable fuel properties such as a lower moisture content, lower ash content, …

This concept of a biorefinery is, however, sometimes not suitable for resources that are already waste when they are collected, e.g., algae deposits on beaches after algal blooms that are collected to avoid the release of H_2S during their decomposition [29,85]. In this case, there is no value product that seems relevant in the current situation. However, with a more developed biorefinery industry, it may be possible to include resources that are today considered as waste.

5.1.2. Consider Co-Gasification with “Dry” Land Biomass, Including Invasive Land Biomass

As presented in this review, the coastal area includes a land area which contains dry resources, particularly dry biomass such as wood, crop residue, plants, … Particularly, there may be invasive species that need to be eliminated and for which gasification could be, as well as producing energy, a permanent treatment.

Co-gasification means mixing two (or more) fuels together, often a traditional fuel with a “new” fuel, and performing gasification in a “traditional” reactor. This is mainly performed in order to perturb, as little as possible, the gasification process with the traditional fuel in a traditional reactor, while including and valorizing as much as possible the “new” fuel. This needs gasification tests with different mixture ratios to determine the optimum ratio based on different parameters such as syngas quality, tar production, fuel conversion, energy efficiency, process disruptions, …

5.1.3. Oxy-Gasification

When it is not possible to reduce the moisture of the fuel by drying, or in a biorefinery process, another possibility is to modify the gasification process itself. Air gasification does not perform well with wet fuel since the drying step in the reactor absorbs part of the heat generated by the partial combustion of the fuel, hence reducing the temperature in the reactor [14]. This temperature reduction decreases the chemical equilibrium constant of gasification reactions, decreasing syngas quality, as well as decreasing tar cracking reactions, leading to a high production of tar with wet fuels.

Dry gasification reactors operate with a fuel moisture in the range of 10 to 25% *w/w* [14].

With the increased moisture of the fuel, the gasification process must be able to increase the oxidation temperature. This can be achieved by increasing the oxygen content in the air, by going up to 100% oxygen feed in the reactor, called oxy-gasification [12].

Oxy-gasification leads to a very high temperature oxidation, which could even damage the reactor walls. However, if the fuel needs drying in the reactor, this would reduce the temperature, plus the presence of steam will act as a temperature buffer. With these operating conditions, syngas composition is enriched in H_2, CO, CO_2, and CH_4, since there is not the dilution by N_2 from the air [12,86]. Syngas concentrations are reported to be 50% *v/v* of H_2, 20% *v/v* of CO, 28% *v/v* of CO_2, and 3–4% *v/v* CH_4 for the oxy-gasification of wet wood (moisture content = 80% *w/w*) [12].

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