Microwave Pyrolysis of Biomass for Bio-oil Production: Scalable Processing Concepts

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Abstract

The pursuit of sustainable hydrocarbon alternatives to fossil fuels has prompted an acceleration in the development of new technologies for biomass processing. Microwave pyrolysis of biomass has long been recognised to provide better quality bio-products in shorter timescales compared to conventional pyrolysis. Although this topic has been widely assessed and many investigations are currently ongoing, this article gives an overview beyond the physico-chemical pyrolysis process and covers engineering aspects and the limitations of microwave heating technology. Herein, we provide innovative scalable concepts to perform the microwave pyrolysis of biomass on a large scale, including essential energy and material handling requirements. Furthermore, some of the possible socio-economic and environmental implications derived from the use of this technology in our society are discussed. Such potential concepts are expected to assist the needs of the industrial bioenergy community to move this largely studied process upwards in scale.

Keywords

Microwave pyrolysis; Biofuels; Biomass pyrolysis; Microwave scale-up; Bio-oil production; Bioenergy

OUTLINE

1. Introduction

The growing demand for energy, depletion of viable petroleum reserves and environmental and socio-political concerns have accelerated the need for the development of sustainable technologies for utilization of biomass. The European Commission recently set a long-term goal to develop a competitive, resource efficient and low carbon bioeconomy by 2050 [1]. Its central vision is the use of renewable raw materials and industrial biotechnology in sectors such as paper and pulp, food and biofuels production, while detecting new growth opportunities considering global challenges and resource constraints [2, 3]. The bioeconomy has already been reported to be one of the most important components of the EU economy and in 2012, was worth €2 trillion in annual turnover [4]; with the bioenergy and bio-based industries representing €100 billion [5]. Approximately 78 million tonnes of biomass feedstock has been projected to be used for biofuel production in the EU by 2020, which is almost twice that used in 2012 [5]. Furthermore, up to 30% of oil-based chemicals and materials are expected to be replaced with bio-based alternatives by 2030 [6]. Such factors have contributed towards a growing focus in the bioenergy research sector over the last few years.

1.1 Biofuels production

Biofuels can be broadly defined as fuels that are derived from biomass (biological material derived from living, or recently living organisms). The most common biofuels are biodiesel and bioalcohols, which include bioethanol and biobutanol [7], otherwise known as 1st generation biofuels. However, such biofuels are produced mainly from food-based crops (sugar and starch based crops [corn and sugarcane] for bioethanol and oil crops [mainly rapeseed oil] for biodiesel [5]). However, issues associated with the impact 1st generation biofuels have on the sources of feedstocks, including the impact they have on biodiversity, water conservation, land use and competition with food crops have raised concerns and implement many challenges that need to be addressed [8]. Furthermore, it is claimed that biodiesel is not a cost efficient abatement for GHG emissions [9].

On the contrary, second generation biofuels are derived from non-food and the non-edible parts of crops (such as wood, agricultural residues) which are usually self-seeding crops that require no fertiliser input and are suitable for growth on marginal lands [10]. As a consequence 2nd generation biofuels may have the potential to overcome the problems associated with 1st generation biofuels as the need for food crops, deforestation and threats to biodiversity are hence reduced. Second generation biofuels have been identified to supply a larger proportion of fuel in a more sustainable manner and with greater environmental benefits [7]. A recent European Council decision restricted the use of 1st generation biofuels to 7% of the energy use in transport for 2020; with the remainder of the target coming from 2nd generation lignocellulosic biofuels [11].

Although the political prospects for 2nd generation biofuels are promising, major developments on available technologies to sustain their production are still needed. Research efforts have focused on the development of different production techniques; for instance, biological, chemical and thermochemical conversion pathways. Biofuels produced by biological conversion (bioethanol, biogas and biohydrogen) generally involve the use of several microorganisms (*e.g. Saccharomyces cerevisiae*, *Methanogenic archae* or *Pyrococcus furiosus*). In the specific case of bioethanol production, the development of an efficiently optimised biomass pre-treatment process is imperative in order to maximise sugar liberation yields, whilst simultaneously reducing the overall cost of the process and minimalising waste production. Moreover, efforts are needed to develop efficient microorganisms with enhanced abilities to ferment hemicellulose-derived pentose sugars [7]. Biogas (i.e., $CO_2 + CH_4$) is a suitable fuel for both the generation of electricity and for transportation [12]. Biohydrogen may be a viable longer-term biofuel, but research is still primitive and has not progressed beyond laboratory scale [13].

Biofuels that are generated by chemical conversion methods include the production of biodiesel from microalgae and oil-based crops *via* transesterification with the co-production of glycerol. The major drawback faced with this approach is the economic feasibility due to the complexity of the primary recovery of bio-oil from algae [14].

Thermochemical conversion technologies involve the thermal degradation of biomass (Figure 1) [15-17]. Biomass can be heated in the absence of oxygen (fast pyrolysis) to ultimately produce an intermediate liquid product known as bio-oil (which may serve as raw material for producing biofuel), or in the presence of an oxidising gas (gasification) to induce the production of an intermediate synthesis gas. Both routes need an additional stage to refine the intermediates for further production of biofuels. For instance, biomass-to-liquid processes have been trialled as a plausible alternative, making use of molecular sieves or transition metal-based catalysts to produce synthetic fuels from syngas [18].

FIGURE 1

1.2 Fast pyrolysis of biomass for bio-oil production

Fast pyrolysis of biomass is a form of pyrolysis technology, and can be used to valorise a broad range of feedstocks ranging from organic wastes to plastics [19] (see Figure 2). Typically, fast pyrolysis involves heating the biomass (previously grinded and dried) up to ca. 500 °C in an oxygen-free atmosphere in very short timescales (~1 s) [20]. As a result of the rapid quenching of the released volatiles during the pyrolysis, a carbonaceous solid residue (char), and a liquid fraction containing high value-added compounds (bio-oils) are obtained. A fraction of non-condensable gases, such as H_2, CO_2, CO and light hydrocarbons are produced. Bio-oils can be co-utilised with conventional fuels, such as coal and natural gas, or can even be a potential substitute for fuel oil or diesel in many static applications including boilers, furnaces and generators [21]. The pyrolysis gas is usually recirculated to the reactor as sweep gas although needs to be re-heated up to the pyrolysis temperature. Energy recovery systems are generally used for this purpose.

FIGURE 2

Fast pyrolysis has been applied as a first step to the production of biofuels, but bio-oils need to be catalytically-upgraded to be used as biofuels [22] (see Figure 3). Raw bio-oils commonly have a high acidity (TAN values 100-200), variable kinematic viscosity (25-1000 m^2/s), large amounts of aqueous phase (15–50 wt%) and a high oxygen content. As a result, these factors lower the energy density within the bio-oil and affect its ability to be used as a fuel and subsequent economic value [20, 23-26].

FIGURE 3

Beyond catalytic upgrading of bio-oils, another promising alternative is the biological conversion (fermentation) of bio-oils [27]. Particularly, sugar-rich bio-oils have the potential to be fermented into valuable biofuels and chemicals. Prosen et al. screened a variety of fungi and yeast for their ability to ferment a levoglucosan-rich bio-oil from wood pyrolysis into ethanol [28]. Ethanol yields were reported to be comparable or better than those from conventional glucose-based substrates (in the case of using *Geotrichum candidum* yeast). Wang et al. investigated the use of the aqueous phase from bio-oil for the production of succinic acid using *Escherichia coli* [29]. Succinic acid has been widely used in the agricultural, food and pharmaceutical industries and is considered as a key platform chemical for the production of biodegradable polymers. The addition of up to 12.5 vol% of the aqueous phase from bio-oil to the fermenting media significantly improved the production of succinic acid as various organic acids and low-molecular-weight compounds (present in the bio-oil) were successfully converted to succinic acid. Liang et al. revealed that the production of lipids from acetic acid-rich bio-oil was feasible using the microalga *Chlamydomonas reinhardtii* [30]. However, a prior step that involved the removal of potential algal-growth inhibitory compounds such as phenols and furfural (in the bio-oil) by adsorption onto activated carbon was a necessary prerequisite.

In spite of the potential of the bio-oil fermentation alternative, improved selectivity of pyrolysis reactions to intermediate chemicals is essential for the success of bio-oil fermentation technologies so as to avoid the production of inhibitors to microorganisms. Regardless of the post-processing bio-oil alternative (*i.e.* catalytic upgrading or fermentation) the keys for the successful implementation of fast pyrolysis technology relies two main criteria: a reduction in cost (the cost of bio-oil has been reported to be 10 to 100% more expensive than fossil fuel [31]), and the improvement of the product quality [7], with both aspects being based on the framework of current pyrolysis processes (Figure 2). Microwave heating has arisen as an emerging and promising alternative which proposes technological solutions to both aspects.

1.3 Microwave heating and the bio-oil production process

Unlike conventional heating, during which energy is supplied to the biomass by heat transfer, microwave heating occurs through the interaction of biomass with the electric field component of an electromagnetic wave (*i.e.* energy conversion takes place instead of conventional heat transfer). Thus, the sample is directly heated, as microwaves provide direct electromagnetic energy transfer leading to volumetric and instantaneous heating [32]. Therefore, microwave pyrolysis of large particles can be performed without the need for an energy-intensive grinding pre-treatment step to achieve reduced particle sizes as shown in Figure 2 for conventional pyrolysis processes [33]. For instance, particle sizes of <2mm for fluidised beds and <6mm for circulating fluidised beds are usually needed [34]. The use of larger particles also avoids complex downstream separation steps to remove entrained solid fines within the bio-oils. Furthermore, microwave heating is very tolerant of water compared to conventionally established pyrolysis technologies (which usually require the moisture content to be below 10 wt%) and may be suitable for most biomass types without the requirement of pre-drying [35, 36]. Although high moisture content may lead to penetration depth issues due to the microwave-absorbing nature of water, a proper microwave applicator can be designed to minimise them. For instance, high moisture diffusion rates to the environment could be achieved by reducing the thickness of the processed biomass layer. In fact, Iribarren et al. reported that the energy input needed for pre-treatment steps accounted for up to a 55% of the energy for driving the entire conventional pyrolysis process [37]. This significant amount of energy could be partially saved as a consequence of implementing a microwave-based pyrolysis strategy, leading to a significant reduction in cost.

Another key factor for the successful implementation of pyrolysis at large scale is the improvement on bio-oil quality. Microwave pyrolysis of biomass has demonstrated the potential to produce a unique grade of products owing to the unique thermal gradients that exist during processing [38-44]. In fact, the exceptional cooler surroundings during microwave heating enables the preservation of much larger amounts of easily-cracking compounds such as carbohydrate derivatives. Figure 4 shows the potential of using microwave pyrolysis to maximise the production of high value-added chemicals from biomass compared to conventional pyrolysis under similar operating conditions. For instance, carbohydrate degradation products such as levoglucosan and furfural are certainly preserved as compared to conventional pyrolysis. Likewise, lignin derived phenolic compounds (creosol, guaiacol, isoeugenol or catechol) are more abundant, which indicates the potential of microwave pyrolysis to minimise secondary fragmentation pathways [45].

FIGURE 4

As a result of the advantages provided by microwave heating to enhance the quality of biomass derivatives, the process flowsheet is much simpler than that of conventional pyrolysis (Figure 5). A cold sweep gas can be used for immediate quenching of pyrolysis products, which is not possible in conventional pyrolysis systems. Hence, further advantages arise from the lack of hot gas handling and energy recovery systems.

FIGURE 5

A number of reviews and scientific articles (Figure 6) have discussed the use of microwaves to induce the production of higher quality bio-oils, mostly from the perspective of optimising the involved operational conditions (*e.g.* microwave power, temperature, residence time or concentration of different microwave susceptors additives). Nevertheless, these studies have not focused on the relevance of this technique for the development of industrial prototypes beyond the commonly used laboratory-scale rigs although some of them have considered scale-up issues [43, 46-51]. Yet the technological transfer of microwave processes to industrial scale is virtually non-existent. Indeed, a lack of data from demonstration plants often prevents successful scale-up because the technical risks have not yet been fully evaluated and mitigated [52].

FIGURE 6

1.4 Goal and scope

The outcomes of previous studies from the microwave pyrolysis of biomass are undoubtedly of benefit to the bioenergy research community. Nevertheless, their usefulness to the industrial processing community is limited as the majority of these studies are not scalable. The aim of this perspective article is critically analyse and evaluate several scalable microwave processing concepts in order to perform the microwave pyrolysis of biomass on an industrial scale whilst preserving and exploiting the inherent advantages of microwave heating.

We focus the discussion on the requirements to scale-up the different microwave processing concepts (see Table 1). The need for high power density (*i.e.* the absorbed power per unit volume of processed material) to release the potential of microwaves on a large scale and induce the pyrolysis of biomass is highlighted. Attention is particularly dedicated to heating uniformity issues, as this must be a key factor with regards to the development of large-scale systems. Hence, a fundamental understanding of the combination of high power density and heating uniformity is essential to ensure the consistent yet reliable production of bio-oils. However, most studies performed at laboratory-scale make use of modified domestic microwave devices operating in a batch mode. These systems have a lack of operating at high power densities and hence, not enough electric field strenghts are attained in order to induce the pyrolysis of biomass [53]. Commonly, microwave susceptor materials are added to the biomass to overcome this problem. The effect of such susceptors on the scale-up of microwave pyrolysis is addressed in this article. Although microwave susceptors may decrease the overall energy consumption of the pyrolysis process, significant drawbacks prevent them from being used at large scale, mainly owing to material handling and process control issues.

Table 1. Requirement specifications for the scale-up of microwave pyrolysis

Requirement	Specification
Power density	High (> 10^7 W/m^3)
Operation mode	Continuous
Volatiles residence time	Very low (< 1 s)
Microwave susceptor additives	None
Cold environment	Highly desirable

To the best of our knowledge, all the studies conducted on the microwave pyrolysis of biomass within the literature are based on batch processing. Herein, we also discuss the highly challenging features of this operation mode to be transferred to large scale and the need for continuous processing as an alternative, along with an overview of some patents on continuous microwave pyrolysis. Accordingly, on the basis of high power density and continuous processing, we propose and discuss new scalable processing concepts;

particularly, the presented models have been classified depending on the means of biomass conveyance across the process. Finally, environmental and socio-economic impacts derived from the use of microwave pyrolysis of biomass are addressed.

2. Development of scalable microwave processing concepts

The scale-up of microwave processes is a compromise between the optimum solution from the perspective of materials handling, electromagnetic engineering and process engineering. To develop reliable microwave processing concepts for biomass pyrolysis, high power density has been reported to be a key criterion to enable for the rapid conversion of biomass without significant heat losses to the surroundings on the basis of batch tests [53, 54]. The dielectric properties of biomass will determine the power density under the influence of an electric field. Typically, the dielectric constant (which represents the ability of a material to store electrical energy) and the dielectric loss factor (which represents the ability of a material to absorb the electric energy) are used to determine the ability of a material to be heated by microwaves.

The power density (Pd) is the amount of absorbed power per unit volume [W/m^3] and is given by [55]

$$Pd = 2\pi \nu \varepsilon_0 \varepsilon'' |E|^2 \qquad \text{Eq. 1}$$

where E is the magnitude of the internal electric field strength (V/m), ε'' is the relative dielectric loss factor, ε_0 is the permittivity of free space and ν is the microwave frequency (Hz). Assuming that all the absorbed microwave energy is converted into sensible heat within the material, the heating rate during microwave heating can be related to the power density according to

$$\beta = \frac{Pd}{\rho C_P} \qquad \text{Eq. 2}$$

where β is the heating rate (*i.e.* temperature variation with time, ºC/s), ρ is the material density (kg/m^3), and C_P is the heat capacity of the material (J/(kg·ºC)). Therefore, the heating rate is proportional to the square of the electric field strength. Previous studies have dealt with the effect of power density on microwave pyrolysis of biomass. J.P. Robinson et al. demonstrated that the efficiency of the microwave pyrolysis of biodegradable wastes was mainly governed by the rate at which energy was supplied to the biomass (*i.e.*, supplied power) rather than by the net input of microwave energy [54]. Correspondingly, the same effect was observed in the case of the microwave pyrolysis of wood pellets. Although an increase in the amount of supplied energy to biomass samples led to higher temperatures –thus, promoting higher bio-oil product yield-, power density had a much greater impact on the pyrolysis process than the total energy input [53]. In fact, a threshold power density of 5 x 10^8 W/m^3 was found below which microwave fast pyrolysis could not be induced. The authors suggested that the pyrolysis process could have been induced by the superheating of bound water within biomass resulting in a large pressure buildup as a result of the higher power density. In fact, the mechanism of microwave pyrolysis is not yet fully understood and needs further investigation, although this is not the aim of this article.

The measurement of temperature during high-temperature microwave processes is highly controversial because of the uncertainty of the measurement [56]. Thus, power density becomes a preferable parameter for controlling the performance of microwave pyrolysis. Beyond this requirement, identification of the most appropriate material handling systems and their electromagnetic compatibility should be the first step in the development of a scalable microwave processing concept. Such evaluation can be based on different categories, as follows:

- *Ease of product separation and gas handling*. The volatile product from pyrolysis which include vapours, microdroplets and polar molecules bonded with water vapour molecules, are usually diluted in an inert carrier gas at relatively low concentrations which induce condensation related issues. Very rapid quenching systems have been suggested to be the most effective alternative to recover bio-oils at large scale [57]. Nevertheless, some systems may present severe difficulties to integrate microwave feed and the removal of pyrolysis products.
- *Control of the residence time of solids and volatiles inside the handling system*. The production of high quality bio-oils is highly dependent on the control of the residence time of volatiles. The removal of pyrolysis volatiles during continuous operation should be conducted rather rapidly (<1 s) to prevent secondary fragmentation reactions within the bio-oils and to maintain an acceptable quality [45, 58]. For instance, fluidised beds can be an efficient technology to blow out volatiles from the reactor by changing the velocity of the fluidising agent. Moreover,

prolonged char residence times are not desirable as char is a highly microwave absorbing material and may induce thermal runaway effects. This would promote gasification reactions between the carbonaceous matrix and the produced volatiles –especially during microwave heating [59-61]– reducing the bio-oil quality.

- *Fouling tendency*. Fouling of the handling system can lead to a decrease in product yields and may cause damage to the microwave hardware (magnetrons and waveguide). Pressure windows are usually employed to separate the waveguide from the microwave cavity where pyrolysis takes place. For instance, fixed bed reactors are more prone to fouling compared to fluidised beds, as no fluidising gas is utilised and thus, heavy oil compounds can easily stick to and accumulate on the reactor walls.
- *Electric field distribution and containment*. Microwave radiation poses electrical hazards which can lead to static electricity build-up and sparks. This can cause damage to microwave hardware and reactor walls. In general, nearby metallic surfaces must be avoided during the design of the system to prevent the dielectric breakdown induced by an excess of a charge buildup over the dielectric strength of the material. The design of a robust container (including suitable microwave filters) remains essential to avoid microwave radiation leakages.

2.1 Batch processing is not a scalable concept for microwave pyrolysis

The vast majority of studies on microwave pyrolysis of biomass have been performed using batch operation mode at low power densities and in the presence of microwave absorbent additives [48]. Nevertheless, the requirement for high microwave power density can be reached in batch reactors. For instance, single-mode applicators can provide high power densities, with extremely high electric field strengths, directly applied to the feedstock material (Figure 7(a)-(b) and 7(d)). Nevertheless, the processing volume is usually very limited because large batch reactors would lead to severe heating heterogeneity and microwaves penetration depth issues (Figure 7(c)). This would result in no direct control of the pyrolysis process and quality of the produced bio-oil.

FIGURE 7

Moreover, batch processing suffers from an increase in mismatching during the process -*i.e.* reduction in the absorbed power, and hence, boost of the reflected power from biomass-. Mismatching is due to the large variations in the dielectric properties of biomass when the temperature increases. The pyrolysis of biomass begins with moisture vaporisation. As water is a good susceptor of microwaves, a sharp decrease in dielectric properties is generally observed beyond 100 °C as water is removed. Then, dielectric properties remain virtually constant once biomass devolatilisation starts, even with an increase in temperature [62]. Char particles, which are extremely high susceptors of microwaves, are then formed at 500 – 600 °C, leading to an important increase in dielectric properties at high temperatures. As a consequence, the thermal runaway effect occurs. This effect is difficult to control and induces the occurrence of secondary pyrolysis reactions, *e.g.* gasification of the char matrix and reforming of valuable chemicals that are present in the bio-oil. Therefore, commonly used microwave susceptor additives to induce the pyrolysis of biomass will not be viable at an industrial scale for bio-oil production, since these additives have demonstrated to lower the temperature threshold of the thermal runaway effect [60]. Furthermore, high amounts of susceptor lead to an undesired heating heterogeneity by reducing the microwaves penetration depth.

Ultimately, such pronounced variations in the dielectric behaviour of biomass during pyrolysis and the sample size constraints, make batch processing not viable as stated in Table 1. Attempts to scale-up the microwave pyrolysis of biomass must be continuous, and this is a common feature which can be understood from the existing prototypes. Table 2 summarises different prototypes of continuous microwave-based systems which have been proposed to perform the pyrolysis of biomass at large scale, although not all of systems have been implemented. To the best of our knowledge, systems presented in references [63], [64] and [65] have already been operated by the authors of such references.

Table 2. Proposed designs in literature (patents and built reactors)

Aim	Process description	Reference
Pyrolysis of organic material, and particularly waste tyre material for fuel-oil production	The biomass is pre-heated by a gas stream up to 250 °C and is then fed to the microwave cavity by means of a belt conveyor, which is separated from the pre-heating zone by a microwave shield. Microwave irradiation is supplied by 3 magnetrons during 15 min. Solids are collected after passing through a purge lock. Additional gas is supplied in countercurrent through the microwave cavity to maintain an atmospheric overpressure.	[66]

Recovery of metals from laminates of metal and organic material	Microwave pyrolysis of laminates of metal and organic materials involves a reactor having a two different chambers with rotary stirrers, each chamber containing particulate microwave susceptor material. Part of the non-pyrolysed organic material from the first chamber is transferred to the second chamber to pyrolyse it allowing the migrating of delaminated metal (*e.g.* aluminium) toward and floating on the upper surface, where the second stirrer allows the fluidisation of the mixture and further metal recovering.	[63]
Microwave pyrolysis apparatus for waste tyres	The designed device consists of a housing including three vertically arranged chambers where feedstock is transported by gravity. The upper chamber serves as a preheating cavity which makes use of the heat generated from the middle chamber, where the microwave pyrolysis is conducted. The lower chamber is the cooling cavity and receives by-products from pyrolysis.	[67]
Study on processing technology for microwave pyrolysis of municipal solid waste	The designed system for microwave pyrolysis consists of a microwave pyrolyzer, buffer tank, diesel oil tourill, alkali liquor absorbing tower and tail gas combustion furnace. Although this study does not mention any detailed engineering aspect such as the type of microwave cavity or feedstock feeding system, magnetrons operate at 20 kW at 2450 MHz frequency. This system has been tested and was found out that material temperature rapidly increases up from room temperature to 350 °C, after which energy consumption increases up to 0.58 – 0.70 kWh/kg because additional energy seems to be needed for the onset of pyrolysis.	[64]
Design, fabrication and operation of continuous microwave biomass carbonization system	This system can process 8400 kg/day of coconut shell, which is fed from the top of the reactor by means of a hopper and is then transported by free fall to a microwave cavity consisting of a 0.847 m^3 cylindrical low cement castable vessel. A multi-feed microwave generators (10 magnetrons) with a total 8.5 kW of microwave power operating at 2.458 GHz is proposed, built and tested. Shutters on the top and bottom of the castable reactor are used to prevent the leakage of microwave radiation.	[65]

Fast pyrolysis and gasification of biomass	No details are provided. Authors only state that this system can include microwave absorbents to significantly increase the heating rate.	[39]

However, detailed engineering reports for these prototypes are not available apart from basic process flowsheet descriptions. Moreover, no reproducibility and accuracy of the data have been presented in the case of the built reactors during the processing period to ensure reliable bio-oil quality.

2.2 Potential scalable microwave pyrolysis concepts

Five different prospective concepts have been evaluated with regards to the scale-up of the microwave pyrolysis of biomass depending on the means by which biomass is transported through the continuous process. These concepts have been previously used in the chemical industry but not within microwave pyrolysis processes. They have been evaluated for their electromagnetic compatibility and ability to deliver enough power density to induce pyrolysis without using microwave susceptor additives. Electromagnetic simulations are presented for each concept for heating at 2.45 GHz using a well-established procedure [52]. COMSOL Multiphysics® 4.4 has been used to determine the 3D distribution of the electric field (V/m) inside the cavity and within the biomass load, and then to calculate the power density (W/m^3) within the biomass. The simulations were conducted using the Electromagnetic Waves Frequency Domain physics interface that can be found under the RF Module. Furthermore, a typical WR-340 port operating at 6 kW has been used. Woodchips were chosen as a model biomass material, with corresponding dielectric properties (ε′=1.83, ε′′=0.12) used to calculate the electric field and power density distribution [68].

2.2.1 Gravity transport: Rotary kiln concept

Rotary kilns have been extensively used within the solid processing industries, such as the cement and concrete materials manufacture industries [69], and have also been used for biomass processing [70, 71]. The feed is usually introduced at one end of the kiln, and the rotating motion enables the processed material to be transported along the length of the kiln to the exit. The rotating motion tumbles the biomass without compressing it, enhancing the mass transfer of volatiles from the biomass particles to the environment. Moreover, this minimises the penetration depth issues that are likely to occur inside pyrolysed material if microwaves can be integrated. In spite of these advantages, microwave rotary kilns have only been contemplated in the case of mineral processing (*e.g.* kaolin and anatase powder) [72]. This patented system (Figure 8) includes a stationary input section (number 14 in Figure 8), a stationary output section (16), and a rotating processing section (18) between those sections. Microwave energy is fed into at least one of the stationary sections (20) through a waveguide (24). The rotating cavity comprises a main body, a microwave absorbing layer (55) –made from SiC or partially stabilized zirconia–, and an insulating layer (18) between the body and absorbing layer –which is composed by non-microwave absorbing materials (Al_2O_3, SiO_2, mullite)–. An important reported issue is the need for a careful design of the exit port (40) to allow the removal of the processed material and to avoid microwave leakages.

FIGURE 8

Figure 9 depicts the electromagnetic evaluation of the rotating kiln concept during the microwave pyrolysis of biomass using the method described in [52]. The tubular cavity includes a feed inlet and two ports to extract volatiles (on the top of the cavity) and char (on the bottom of the cavity) (see Figure 9(a)). Such configuration induces a high electric field strength at the centre of the kiln, which is relatively low at the outer edges (Figure 9(b)); hence, the biomass (which is accumulated within the outer edges as a result of the rotating motion) would not be subjected to as high electric field intensities. Power density is shown to be maximum at the edges of the material in the radial plane (Figure 9(c)); moreover, the feed inlet area is subjected to the highest power density where two hot spots can be clearly detected (Figure 9(d)). Although this appears to be very uneven, the rotating action of the kiln enables the biomass to pass through at least one area of relatively high power density.

FIGURE 9

A similar system was proposed by P. Veronesi et al. to process 60 kg/h of tyre wastes for the production of activated carbon, although operating in batch mode [73]. This reactor has a cylindrical shape and incorporates a stirring system made of metallic blades rotating coaxially to the main applicator axis (hence, simulating a rotary-like kiln). A 12 kW 4-ports was used and a pressure window was designed to lower the overall reflected power; crosscoupling between magnetrons being negligible during the process duration. However, the presence of metallic parts was observed to lead to overheating of the nearby material.

A highly challenging feature of the rotary kiln is the integration of the microwave feed and the removal system to separate char and volatiles during continuous operation, being necessary to avoid microwave radiation loses to the environment. Furthermore, it is not an easy task to meet the required low residence time of volatiles to prevent secondary reactions according to the requirements in Table 1. It is difficult to provide a sufficient cold environment within this concept, as a result of which degraded bio-oils would be produced.

2.2.2 Conveyor transport: Conveyor belt concept

The conveyor belt system has been widely used throughout the drying and food processing industries [74-76]. To integrate a conveyor belt into a continuous microwave processing system while maintaining high and even power densities across the cavity geometry, a tunnel applicator was proposed by incorporating a ‘self-cancelling’ reflection step (see Figure 10) [77]. This concept aimed to process oil-contaminated drill cuttings, by transporting them through a tunnel on a microwave-transparent conveyor belt (Figure 10(a)). However, achieving a uniform electric field throughout the depth of process material is not trivial. An elegant solution consists of inducing a number of overlapping regions of high electric field intensity (three hot spots in Figure 10(b)) by using a self-cancelling reflection step positioned at an offset distance from the centre of the waveguide with a depth equal to one quarter of a wavelength.

FIGURE 10

Figure 11 shows the power density distribution across the volume of the conveyor belt when this concept is transferred to pyrolysis processes. Power density across the cavity width is shown in Figure 11(a) and three hot spots of high power density can be attained along the length of the applicator, the position of which depending on the dielectric properties of the biomass and the underlying belt. Such confined power distribution allows for a better heating homogeneity compared to biomass processed by means of the rotary kiln.

FIGURE 11

Biomass processed through the conveyor belt concept can then be subjected to power densities much higher and uniform as compared to the rotary kiln concept (higher by 2 orders of magnitude). Moreover, the residence times can be very short, which is of extreme importance in promoting fast pyrolysis, and the evolved volatiles from the pyrolysis process can be easily extracted by means of a fan through a series of specially designed perforations in the top of the cavity. A further advantage of this microwave processing concept is that the thermal inertia is very low; hence, start-up and shut-down of the process can be achieved within seconds.

Nevertheless, important challenges can be detected for this system. On the one hand, the design of electromagnetic chokes structures to limit the microwave leakage through the open feed boundaries, so as to allow the feed material and products to pass continuously through the cavity but containing the electromagnetic field is highly challenging. On the other hand, the compatibility of the belt material with microwave processing must be addressed; the belt material should be microwave transparent, mechanically robust and thermally stable as high temperatures are promoted. Basalt fibres and non-coated glass fibres can meet those requirements to develop the process [78]. Nevertheless, the need for flexible conveyor materials is incompatible with the high temperature nature of the process. The use of a rigid conveyor is then established in the following concept.

2.2.3 Conveyor transport: Rotating ceramic-based disc concept

The rotating disc concept is similar to the conveyor belt but biomass is instead brought into a circular conveyor system. Particularly, biomass can be processed inside a channel created by static metal walls attached to a circular disc, which can be separated and cleaned outside the processing area, mitigating fouling issues that are highly likely to happen in the previous presented processing concepts. Figure 12(a) shows the prototype concept [79, 80]. The biomass is separated from the circular turntable by means of a microwave-transparent rotating window (blue-coloured in Figure 12(a)), made from *e.g.* alumina, which behaves as a shield from damage to magnetron. Microwave feeding may be conducted underneath the microwave-transparent rotating window, to prevent the waveguide from volatiles contamination, which could lead to power being absorbed within the protecting window causing its breakage. Furthermore, a waveguide coupled to the top of the reactor would inhibit volatiles extraction from the area where most of them are generated (*i.e.* above the region of highest power density, see Figure 12(b)).

FIGURE 12

The rotating ceramic-based disc concept is then able to induce a precisely controlled electric field distribution and high power distribution within a narrow geometry as compared to rotary kilns and conveyor belts (see Figure 12(b)). This concept has been recently patented [80] and transferred to industry (see Figure 13). A visual inspection of the resulting biomass after microwave pyrolysis is sufficient to appreciate the similarities with the electromagnetic simulations, as biomass was pyrolysed within the simulated area corresponding to the peak power density. As in the case of the conveyor belt concept, an important advantage of the rotating ceramic-based disc concept is its simplicity to control the residence time of biomass by adjusting the rotation speed.

FIGURE 13

Metallic moving sections are needed within the microwave applicator to allow the biomass to be transported and for cleaning purposes. Nevertheless, their presence within the heating zone prompts a high likelihood of arcing between the moving parts, which could induce undesirable thermal runaway of biomass. A careful electromagnetic design must then be carried out to prevent arcing effects, and electrical contactors are required in regions of high electric field intensity.

2.2.4 Pneumatic transport: Microwave fluidised bed concept

Fluidised beds have been successfully used in different processing areas such as petroleum refineries to convert the high-boiling hydrocarbon fractions of crude oils to valuable gasoline and olefinic gases [81], coking of petroleum residues [82], roasting of sulfide ores [83] or calcination of limestone [84]. Particularly, pyrolysis of biomass at large scale has also been conducted by means of fluidised beds as they are able to provide the large amounts of heat required for pyrolysis [85]. Furthermore, a homogeneous temperature can be reached because solid particles are perfectly mixed, enabling an efficient convective heat transfer and thus heating homogeneity [86]. However, indirect heating must be used to obtain high quality bio-oils instead of *in-situ* heating (*e.g.*, hot carrier gases may promote bio-oil degradation) unless circulating fluid beds are used [87]. Commercial scale reactors then require heat exchanger tubes through which hot gases (generated by the combustion of gaseous or solid by-products from the pyrolysis reaction) flow. Furthermore, fluidised beds have the great advantage of easy integration with separation and vapour recovery systems as compared to other material handling systems. However, the fluidisation behaviour is highly dependent on the type of biomass and particle size. For instance, hardwoods have a fibrous shape which makes the particle stick to each other during the gas flow; channelling and slugging behaviour being induced even at low gas velocities. Henceforth, previous biomass pelletisation pre-treatment could be required.

As indirect heating should be used to preserve the product quality, microwave heating may be contemplated as an appropriate alternative. The scalable processing concepts already presented in this perspective article have shown different opportunities for controlling the heating homogeneity. Nevertheless, a suitable strategy for controlling arcing effects in order to avoid biomass thermal runaway has not yet been assessed. In this regard, fluidisation would greatly help to improve the heating homogeneity because of the use of a cold fluidising agent inducing biomass particles to be continuosly transported between hot and cold spots within the bed. Microwave fluidised beds have been used for drying purposes [88]. Generally, reduced drying time (by ca. 50%) and lower final moisture contents are attributed to the microwave heating under similar conditions, owing to the fact that the volumetric nature of microwaves increase the moisture diffusivity and thus, the transport of water from the biomass core to the environment can be enhanced [89]. H.C. Kim et al. proposed the use of a microwave fluidised bed reactor for the fast pyrolysis of chlorodifluoromethane into tetrafluoroethylene [90]. This technology showed to be highly promising for that particular reaction as a high heat flux through the reactor volume was achieved without overheating the reactor wall. Recently, Q. Xie et al. put forward a new concept of microwave-assisted dual fluidised bed gasifier [91]. The basic idea of this gasifier is to divide the fluidised bed into two zones; *i.e.* a gasification zone and a heating zone. A circulation loop of bed material (SiC microwave absorbing) is then created between these two zones. SiC acts as a heat carrier from the heating zone to the gasification zone allowing the thermal degradation of biomass in the gasification zone. Nevertheless, this concept has not been demonstrated yet and is devoted to the production of a high quality syngas (H_2+CO) instead of bio-oils.

The electromagnetic evaluation of the fluidised bed concept (shown in Figure 14) for biomass pyrolysis is shown in Figure 15 [68]. The biomass particles are processed inside a microwave transparent column attached with a disc acting as a distributor for the fluidising gas. This column has to be placed inside a carefully designed cavity to avoid contact with the cavity walls as this would create areas of high electric field intensity near the edges, leading to a high likelihood of arcing.

FIGURE 14

FIGURE 15

An extremely high power density can be achieved through a very confined region containing the biomass (see Figure 15(b)). This process was recently proposed by M. Adam et al., who determined that an absorbed power of 0.75 kWh/kg$_{biomass}$ (using 6 kW as input power) would be enough to achieve power densities as high as $7 \cdot 10^7$ W/m^3 within sycamore-derived biomass and induce the pyrolysis process [68]. This compares well with the energy requirements reported for microwave pyrolysis of woodchips in a fixed bed (0.6–0.7 kWh/kg$_{biomass}$) in order to pyrolyse to a level comparable with conventional pyrolysis [92], although avoiding thermal runaway effects.

2.2.5 Extrusion transport: Auger reactor concept

Although fluidised bed reactors are well understood, provide high biomass throughputs and bio-oil yield, their operation relies on a large volumetric flow of carrier gas that must be heated and compressed, at least within conventional pyrolysis plants. Extrusion-based systems, such as the auger reactor have attracted interest for pyrolysis application as they can be operated continuously with almost no carrier gas [93-95]. Multiphase systems (*eg*, within pyrolysis processes) can be processed by means of the rotation motion of one or multiple screw conveyors inside the reactor (see Figure 16). This mixing motion enhances the heat transfer between solids, liquids, gases and the reactor wall, as well as the transportation of the particles towards the reactor outlet. Further biomass particles can be fed and pyrolysed while char particles leave the reactor, this allowing a continuous operation.

FIGURE 16

A. Veses et al. proposed an energy self-sustained system to perform the catalytic pyrolysis of woody biomass in an auger reactor pilot plant [96]. Calcium-based catalysts enabled *in-situ* bio-oil upgrading and reduced the circulation of a sand-based heat carrier. The auger pyrolyser can then be especially appealing for its potential to reduce operating costs associated with bio-oil production. Y. Li et al. used a dual-stage system based on an auger pyrolysis reactor (internal diameter, 150 mm; length, 3 m), and a downstream fixed-bed zeolite-based reactor operating in a continuous mode to process 20 kg/h of a solid residue from bio-ethanol production process [97]. Unfortunately, temperature gradients of ca. 100 °C were observed due to the low heat transfer efficiency from the walls of the auger reactor to the biomass. Interestingly, the pyrolysis vapours were extracted by means of a vacuum pump with a tuneable flowrate, making this possible to regulate the residence time of such volatiles.

Extrusion-based systems have previously been shown to be compatible with microwave processing. The company AMB Ecosteryl sells a prototype able to inert up to 175 kg/h of medical wastes by means of a screw conveyor which is embeded into a microwave-heating tunnel composed of six magnetrons of 2 kW, being consumed up to 0.48 kWh/kg_{wastes} [98]. The Center for Biorefining from the University of Minnesota (in collaboration with UMB-IMT and X-Waste International) developed a 4.5 kW microwave pyrolysis reactor able to process 10 kg/h of biomass based on an auger transport system although no more information has been reported to date about the behaviour of this system during operation neither on cavity materials [99]. A recent patent put forward the extraction of hydrocarbons from chippings or the like produced during the formation of a borehole by means of a microwave extrusion system [100]. This last concept could be applied to the microwave pyrolysis of biomass as shown in Figure 17. The concept consists of two twin steel screws having 2.5 m length which enables the transport of biomass into the rectangular cavity where microwaves are fed underneath the ceramic cavity by means of a tapered waveguide. A high power distribution can be induced and focused in a single spot, reasonably uniform across the entire biomass sample volume, which makes this concept highly controllable. From Figure 17(a) it can be inferred that microwaves are not transmitted to the area containing the conveyor screws (white areas) and are only absorbed by the biomass.

FIGURE 17

Although the rotation speed of screws can be controlled to meet the solids residence time specifications for microwave pyrolysis, this concept require ceramic components for the walls able to withstand temperatures higher than 500 ºC and resistant to fouling from the produced bio-oils. This feature was overcome when using drill cuttings owing to their slurry nature. Perhaps, the use of liquid additives to biomass may well aid to scale-up the extrusion concept for microwave pyrolysis.

Before discussing the environmental and economic impacts derived from the implementation of large scale microwave pyrolysis plants, Table 3 summarises the main technical findings from the scalable concepts presented along this article.

Table 3. Technical comparative evaluation of the scalable concepts for microwave pyrolysis

Concept	**Advantages**	**Disadvantages**
Rotary kiln	• Rotating motion promotes the heat and mass transfer from solid particles to environment	• Uneven and low power density distribution • Long residence time • Difficult to provide enough cold environment
Conveyor belt	• High power densities • Very low residence time • Low thermal inertia: good control	• Flexible belt material at high temperatures required
Rotating ceramic-based disc	• Extremely high power densities	• High likelihood of arcing between moving parts

	• Extremely confined power densities • Very low residence time • Rigid conveyor	
Microwave fluidised bed	• Extremely high power densities • Reduced likelihood of arcing	• Feedstock size may prevent fluidisation
Auger reactor	• Highly localised power density distribution • Sweep gas avoided	• Excessive fouling from the bio-oils

3. Prospects for microwave pyrolysis of biomass

Existing large-scale bioenergy production systems including pyrolysis and gasification facilities are still relatively expensive to operate compared to fossil-based facilities and face some non-technical barriers when trying to penetrate the energy markets. A.V. Bridgwater et al. stated that fast pyrolysis systems have a great potential to generate electricity at a profit in the long term, and at a lower cost than any other bioenergy-based system at small scale [31]. Nevertheless, profitability in the short term could be achieved by exploiting specific niches and features of fast pyrolysis, such as small-scale combined heat and power facilities. For instance, a distributed bioenergy production strategy was proposed by Ruan et al [101]; a microwave-based scalable technology was suggested to be implemented on average-size farms to pyrolyse crop residues. This strategy poses interesting features such as an affordable capital cost (*e.g.*, 1500 times lower as compared to a cellulosic ethanol plant), low transport cost (as this is a portable system) as well as the fact that rural communities can be benefited both economic and socially. Nevertheless, we can say that the future of microwave-based bioenergy technologies is not clear and embraces multifaceted environmental and socio-economic issues associated to the production and consumption of bio-derived products and competitive breakthrough technologies. Rather than giving a full technical study about microwave pyrolysis issues, we aim to focus on ongoing discussions around their impact in different aspects of our society.

3.1 Environmental impact and sustainability

The bioenergy industry provides a promising energy alternative to conventional fossil-based fuels which can significantly reduce greenhouse gas emissions [102]. Particularly, thermochemical conversion processes involves the usage of heat, electricity and/or additional fuels and chemicals whose impact upon the environment should be fully addressed. In order to identify potential environmental impacts of end products from pyrolysis of biomass and, particularly from microwave pyrolysis, *Life Cycle Assessment* (LCA) analyses can be applied as a useful tool [37, 103, 104]. LCA consists of a set of standards gathered under the ISO 14040 series which follows four basic steps: 1) goal, scope and system boundaries definition; 2) life cycle inventory analysis; 3) life cycle impact assessment; and 4) interpretation of the result. M. Patel et al. recently identified pyrolysis as the most widely thermochemical studied process when it comes to LCA [105]. In this sense, three major phases are generally included to delimit the system boundaries: 1) biomass planting, harvesting, and transportation; 2) pyrolysis plant site operation and upgrading of primary products; and 3) demolition and recycling of the pyrolysis plant. Beyond common issues to all bioenergy strategies, such as soil erosion or biodiversity protection, global warming potential is usually the most reported environmental impact within LCA of pyrolysis processes, followed by acidification and eutrophication in terms of CO_2, SO_2 and PO_2 equivalents, respectively.

A recent study presented a very detailed evaluation of several environmental impacts during the pyrolysis of poplar to produce transportation fuels [37]. The authors revealed that the biomass pre-treatment steps (biomass crushing, grinding and drying) accounted for the highest contributions to acidification, eutrophication and photochemical oxidant formation, with percentages ranging from 28% to 67%. In addition, pre-treatment steps also led to the highest contribution to global warming potential (nearly 1.5 tonnes of CO_2 equivalent per tonne of produced biofuel). Q. Yang et al. recently studied the greenhouse gas emissions from a pyrolysis plant in China [106]. High electricity consumption was pointed out as the main factor affecting the total greenhouse gas emissions and, yet again, biomass pre-treatment steps (drying and molding) were found to be 70% responsible for them; pyrolysis only representing a minor influence. The use of exhaust gases to carry out the drying step would reduce these emissions. Definitely, the pre-treatment of biomass is an energy-intensive step which could be partially avoided when using microwave pyrolysis due the unique features of volumetric heating [39, 59]; thus, allowing a decrease in the global warming potential of the whole process if electricity is provided by means of fossil-based fuels. Also, the production and pre-heating of fluidising gas as a previous step to fluidised bed pyrolysis plants increase the greenhouse gas emissions. M. Shemfe et al. reported a significant impact of the nitrogen flowrate fed to the reactor when the means of production is taken into account; an increase of 50% in nitrogen gas feed gave rise to an increase of 44% in greenhouse gas emissions [107]. These results give room to a significant growth on sustainability when microwave pyrolysis has to be implemented at large scale as no pre-heating seems to be necessary [92]. In spite of the potential for improved performance from an environmental point of view, only one study on LCA of microwave pyrolysis has been found within literature and it is focused on the production of syngas instead of bio-oils, and only based on an energetic point of view [108]. In that article, the authors revealed that the most energy-consuming steps were the biomass transportation to the plant and the pre-treatment steps, regardless of the means of producing bioenergy (radio-frequency plasma, microwave-induced, downdraft gasifier or plasma torch systems). No further results were presented to discuss the environmental impacts of microwave pyrolysis. Nevertheless, the energy assessment conducted (known as *Net energy balance* [NEB]) was highlighted as an important concept when choosing a bioenergy processing platform because only a process having a high positive NEB can be considered as economically and environmentally sustainable [109].

3.2 Economic impact

A number of studies have been performed to understand the techno-economic implications of fast pyrolysis plants for bioenergy production. A.V. Bridgwater et al. compiled normalised plant costs and established several correlations to estimate the total plant cost and electricity production costs from fast pyrolysis depending on the biomass feed input and output flowrate of bio-oils [31]. Calculated capital costs ranged from 1.09M€ when processing

200 kg/h of dried biomass to 6.95M€ at 4000 kg/h of dried biomass (base year, 2000). Nevertheless, these costs were updated 11 years later and were reported to range between 2.37M€ and 16.67M€ by feeding the same biomass flowrates [20]. In the case of the costs for producing electricity, these ranged from 0.073€/kWh at 20 MW_e rising to 0.146€/kWh at 1 MW_e in 2000, converging at the larger scale with the average electricity price paid in the EU by a large consumer. Systems de-coupling was contemplated as a competitive alternative for bioenergy production; particularly, the option of de-coupling fast pyrolysis step and diesel engine generation step was reported to be the least expensive option up to 5 MW_e, as compared to three other de-coupling scenarios: combustion and steam cycle modules, gasification and diesel engine, and pressurised gasification and gas turbine combined cycle. Several studies have been also performed to determine the production cost of electricity from different thermochemical conversion technologies and interestingly, these costs remain within close limits regardless of the technology employed [110-112]. Other studies have gone beyond by calculating the production cost of the biofuels by including upgrading steps. For instance, gasoline and diesel might be produced from fast pyrolysis of corn stover at 0.57-0.84 €/L (2014 USD based) [113, 114], which are prices a bit higher than those reported for fossil-based fuels, 0.45-0.54 €/L (2016 USD based) [115].

However, very limited information is available on the economic evaluation of microwave pyrolysis of biomass to determine its viability. Only L. Wang et al. reported a techno-economic analysis on microwave pyrolysis of Douglas fir pellets to produce aromatic hydrocarbons enriched bio-oil [101]. They estimated an annual profit of €120,000 by using a transportable small-scale system. Nevertheless, the authors stated several limitations of their analysis owing to the lack of large scale operation data and contingency factors. Besides, the impact of key variables on return of investment of the plant was assessed. The capital cost was found to be a particularly important sensitivity variable due to the existing uncertainties; furthermore, the resulting bio-oil yield and bio-oil selling price were pointed out to be the variables with higher impact on the rentability of this process. The capital cost of microwave hardware is of the order of €1000−2000 per kW of installed power, much higher than conventional heating equipment [90]. Nevertheless, there is likely to be significantly less capital expenditure required on other stages within the process and lower labour requirements given the reduced number of unit operations as pointed in Section 1.3. Anyway, this techno-economic analysis show that this technology, once commercialised and in widespread operation, can create jobs and bring added incomes to operators, opening up a new frame for farmers to participate in the bioenergy industry.

The strategy of distributed microwave pyrolysis was later used as a means of placing small-scale reactors at biomass-derived waste production sites for *in-situ* processing [116]. Positive socio-economics prospectives were associated to this strategy. For instance, the syngas generated could have numerous applications, such as heating, water heating, and cooking within residential areas, being an economical incentive to the user. Moreover, the densification of biowastes when pyrolysed would make the cost of by-products collection significantly lower, creating direct cost savings to the users as compared to the actual waste management scheme. As expected, the authors stated that beyond a certain scale, the transportation costs can overcome the positive effect of scale economies for centralised plants; nevertheless, they unexpectedly proposed the existence of an *inflexion point* at considerably smaller scale below which an economically viable model for microwave pyrolysis of biowastes could be reached by considering a distributed strategy.

The energy balance involved in the microwave pyrolysis of biomass is also an important issue which might tip the balance in favour of the future industrialisation of the technology beyond the product quality. Nevertheless, this is not usually reported within literature. Only one paper discusses the benefits of microwaves on pyrolysis of straw feedstock [117]. The minimum microwave power was found to be about 0.371 kW·(kg straw)$^{-1}$ and the ratio of heat loss and conversion loss of electricity to microwave energy occupied in the total input energy was 42% (balancing against the energy content of the char, bio-oil and gases). From the results presented in such study, one can derive that the energy efficiency of microwave pyrolysis of wheat straw is 79.8% (ratio between biofuel energy and sum of energy required for pyrolysis plus energy content of biomass). Nevertheless, the energy recovery from the raw biomass resulted in 91%, which is quite much higher than the energy recovery from similar biomass feedstock by means of conventional flash pyrolysis technologies (35-39%) [118]. In the same regard, Y. Fernandez et al. compared the energy recovery from the pyrolysis of coffee hulls by means of conventional and microwave means [119]. At 500 ^{o}C, the energy recovery from conventional pyrolysis was 84%, whereas it increased up to 99% using microwave technology. These results are evidently not enough to draw a final conclusion upon the energy efficiency of industrial scale of microwave pyrolysis plants. A comprehensive energy audit should be conducted in a real industrial scale pyrolysis plant, and more importantly, those studies need to be considered on a case-by-case basis to determine whether the economics are viable. Nevertheless, improvements in the system can certainly improve the energy efficiency, and here is where the powerful electromagnetic design tools presented in this article can play a key role, thus making use of the microwave irradiation in a more efficient way by means of improved microwave power distribution within the cavity reactor.

In summary, a careful consideration of the investment possibilities and financial assumptions, processing capacity, biomass feedstock alternatives, product options, operation costs, land costs, and revenues will determine the implementation of microwave pyrolysis at large scale –or even distributed small scale– orientated to specific bioenergy markets, always depending on the role of governments creating the necessary incentive and instruments.

4. Conclusions

In spite of the potential technological advantages provided by the use of microwaves to drive pyrolysis processes, there is still a large gap between laboratory research and commercial production. Extremely limited scale-up attempts and thus, a scarce number of scientific studies conducted at large scale within literature have been performed up to date. Nevertheless, some potential processing concepts have now been proposed under the paramount requirements of high power density and continuous operation mode. In this regard, electromagnetic simulations are a powerful tool which can be extremely helpful to predict the extent of the pyrolysis process.

The guidelines presented in this article can provide the bioenergy industry the decision-making concepts needed to establish microwave heating processes, and its prospectives to deliver step-changes and open up new markets at an increased sustainability. The need for a multidisciplinary approach is essential for the subsequent integration of process, electrical and electromagnetic engineering disciplines.

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Figure captions

Figure 1. Biomass pyrolysis and gasification routes for the production of synthetic gasoline and diesel.

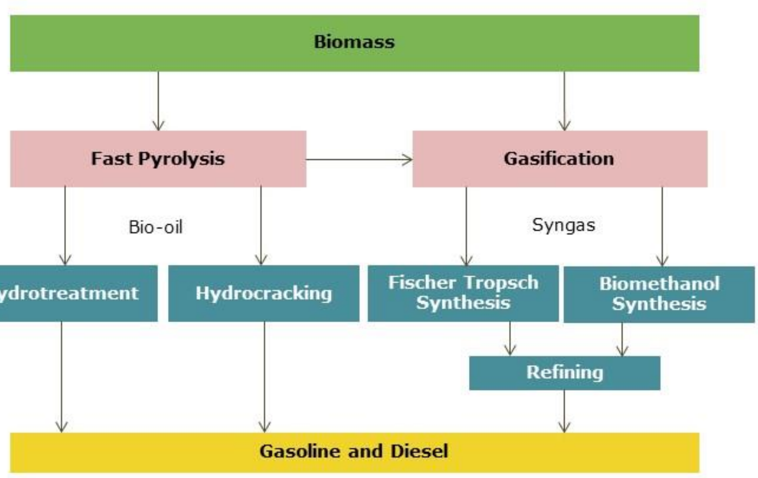

Figure 2. Fast pyrolysis process flow diagram.

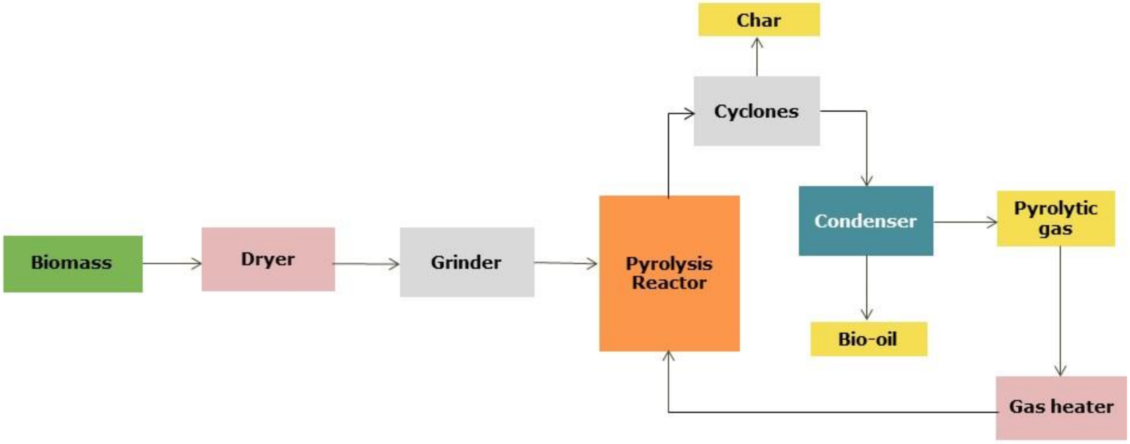

Figure 3. Chemical reactions involved during bio-oil catalytic upgrading. Biomass-derived compounds (green) present in bio-oils; desirable compounds after upgrading (blue). DCO (decarbonylation, decarboxylation), CRA (cracking), HCR (hydrocracking), HYD (hydrogenation), DDO (direct deoxygenation), DAO (dealkoxylation), DME (demethylation), OMT (methyl transfer reaction) and HDO (hydroxygenation). Reproduced with permission from [22].

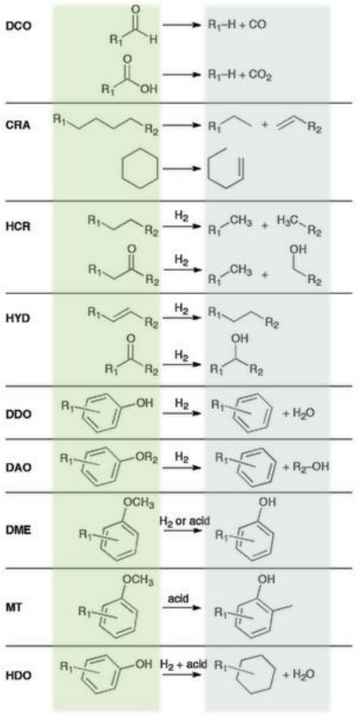

Figure 4. Organic compounds analysed by means of GC-MS from bio-oils obtained from larch woodchips by means of olivine-catalysed pyrolysis in a fluidised bed (conventional pyrolysis) and from microwave pyrolysis in a fixed bed (microwave pyrolysis). Data extracted from [92].

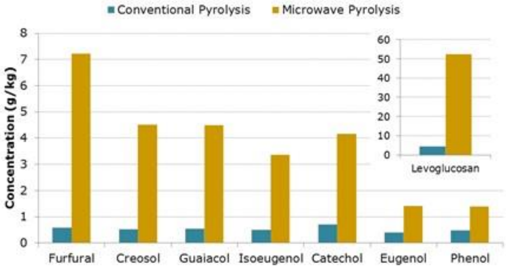

Figure 5. Microwave pyrolysis process flow diagram.

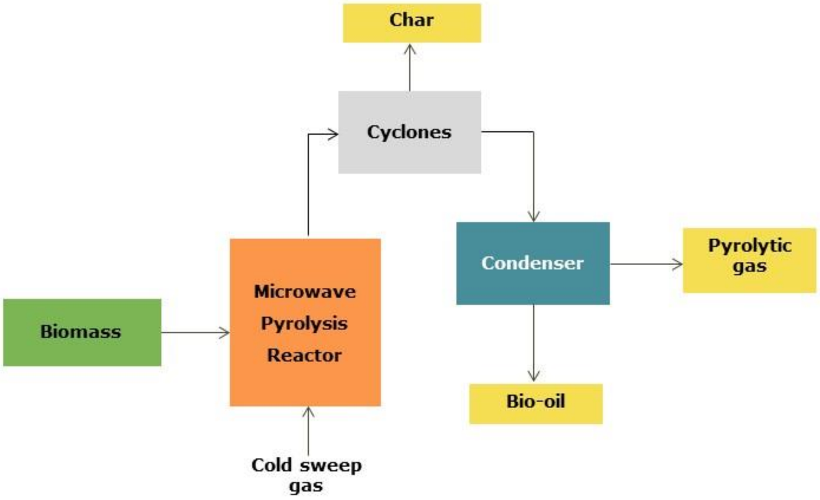
Char
Cyclones
Condenser
Pyrolytic gas
Biomass
Microwave Pyrolysis Reactor
Bio-oil
Cold sweep gas

Figure 6. Evolution of the number of scientific publications related to microwave pyrolysis during 1968-2015 period (keywords: ‘microwave’ AND ‘pyrolysis’) (Source: Scopus®).

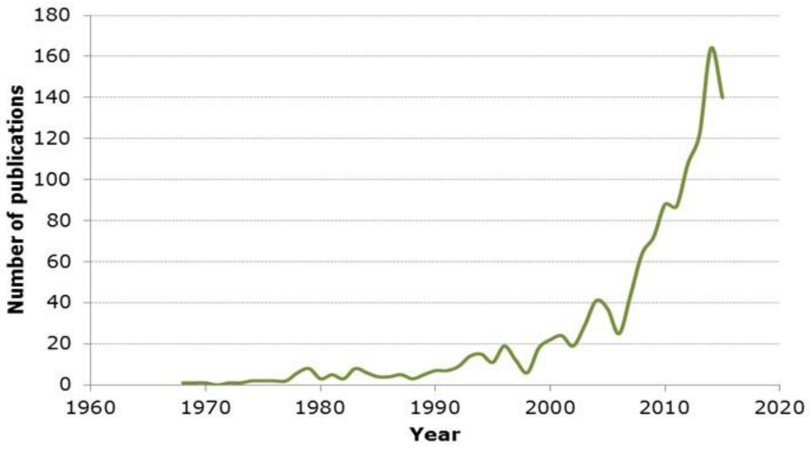

Figure 7. Batch processing features: (a) Electric field and (b) Power density distribution within a single mode reactor for pyrolysis of coal; (c) Heating heterogeneity from microwave pyrolysis of woodchips due to large-sized samples. Reproduced with permission from [92, 120]; (d) Single mode cavity.

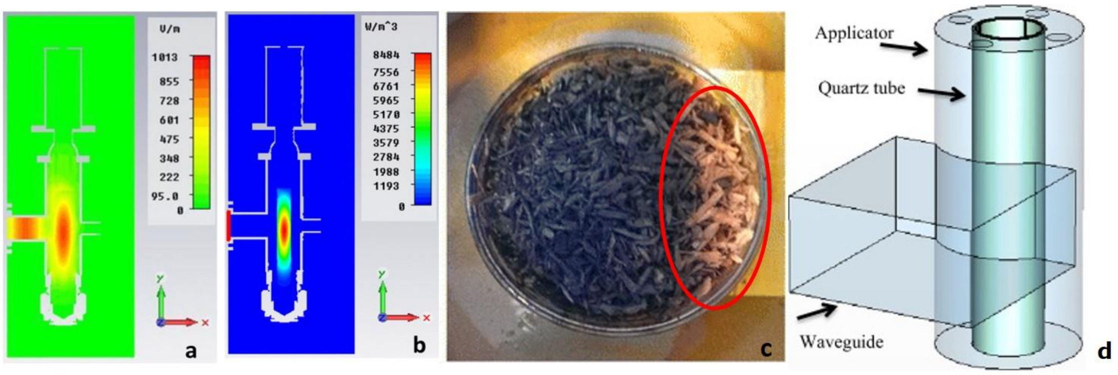

Figure 8. Cross-sectional view of the embodiment of a patented rotary microwave kiln apparatus [72].

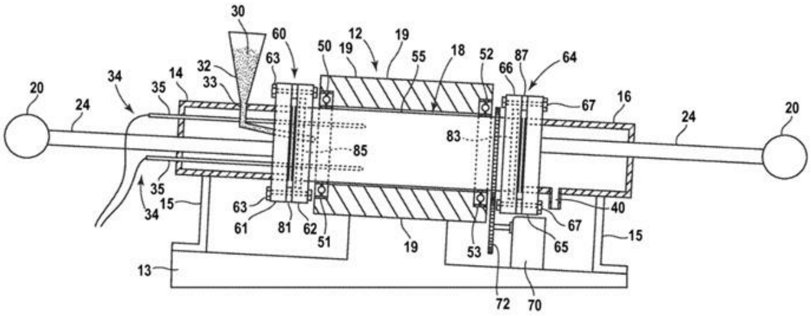

Figure 9. Electromagnetic simulations for microwave pyrolysis in a rotary kiln: (a) Schematic of the dimensions (length, 1 m; diameter, 1 m) including biomass distribution (purple volume); (b) Radial electric field distribution (V/m); (c) Radial power density distribution (W/m^3); and (d) Power density distribution along the length of the kiln (W/m^3).

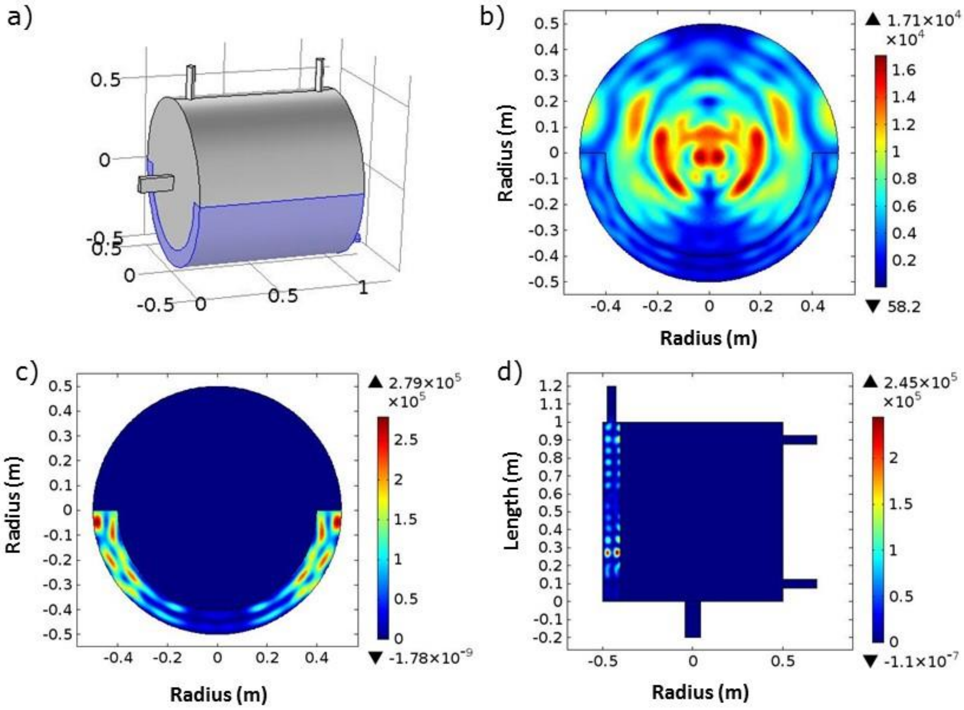

Figure 10. Conveyor belt processing concept: (a) Tunnel applicator; and (b) Effect of self-cancelling reflection step on the power density distribution. Reproduced with permission from J. Robinson et al. [77].

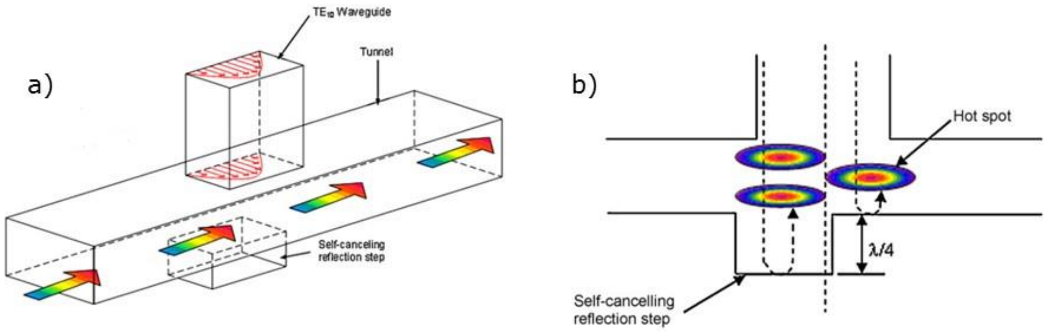

Figure 11. Electromagnetic simulations for microwave pyrolysis of biomass in a conveyor belt: (a) Power density across the applicator width (W/m^3); and (b) Power density across the applicator length (W/m^3). Dimensions of the tunnel: length, 3 m; width, 0.01 m; height, 0.1 m. Dimensions of the biomass layer: length, 3m; width, 0.01m; height, 0.06 m. Self-cancelling reflection step is positioned at an offset distance of 0.02 m from the centre of the waveguide. Only the section between length 1.2 m to 1.8 m has been depicted as the remaining length had negligible power density.

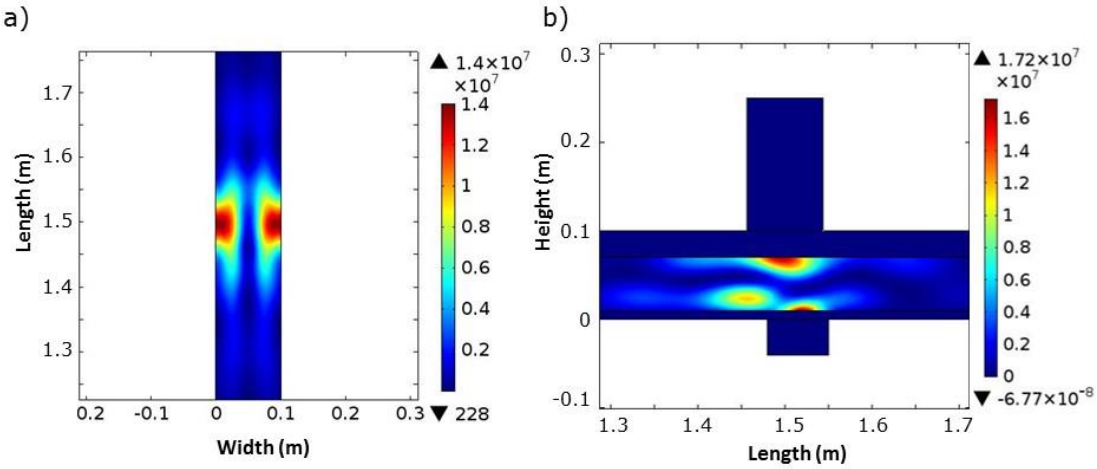

Figure 12. Rotating ceramic-based disc concept: (a) Geometric model (disc diameter, 2 m), including a tapered waveguide; and (b) Power density distribution (Scale: MW/m^3).

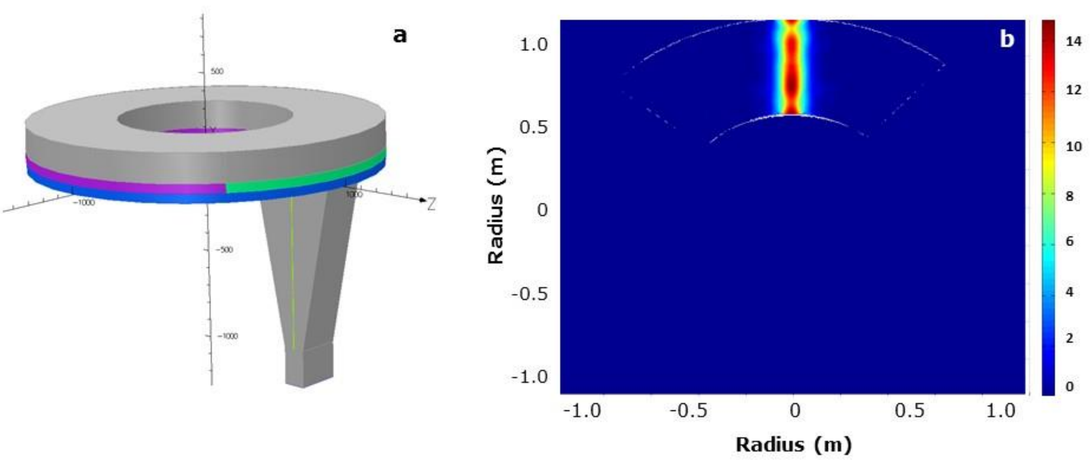

Figure 13. Scaled-up rotating ceramic-based disc concept: (a) Developed prototype for Scandinavian Biofuel SBC2 company; (b) Raw biomass within the circular trough; and (c) Pyrolysed biomass after microwave heating [79].

Figure 14. Schematics of the microwave fluidised bed concept.

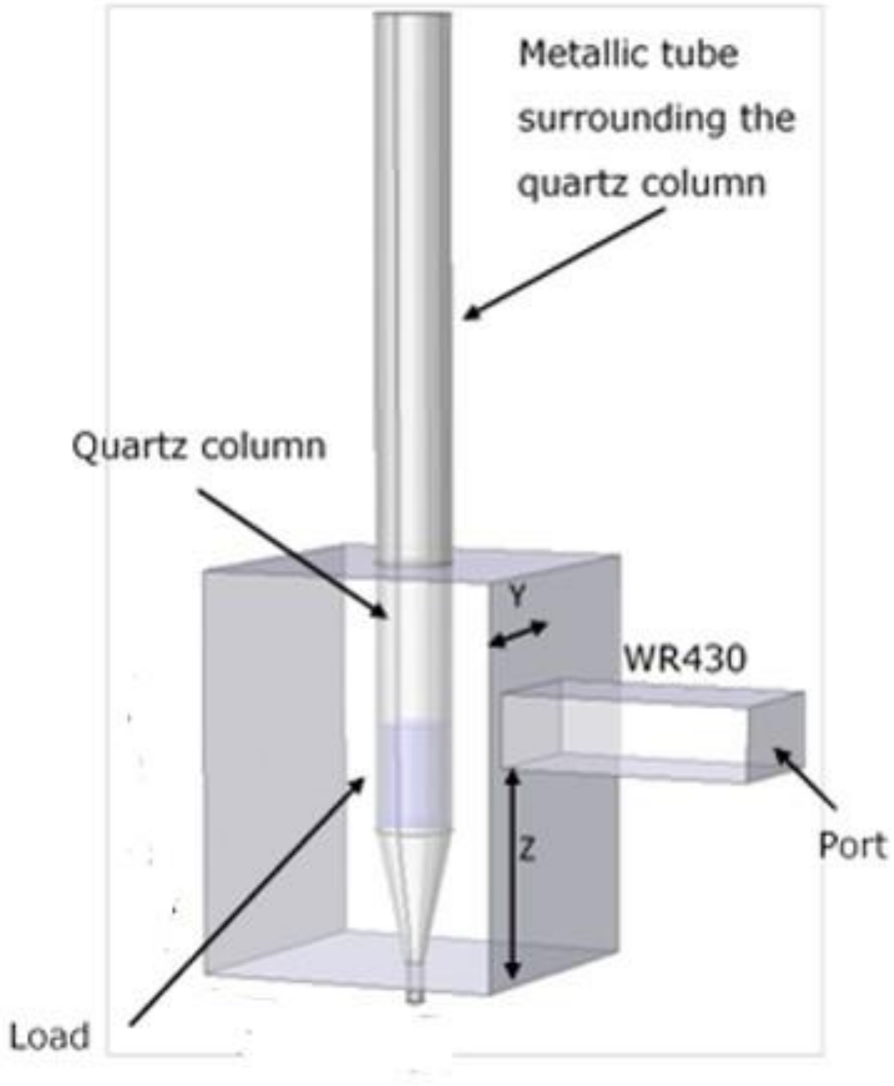

Figure 15. Microwave fluidised bed concept: (a) Electric field distribution (V/m); and (b) Power density distribution inside the cavity (W/m^3).

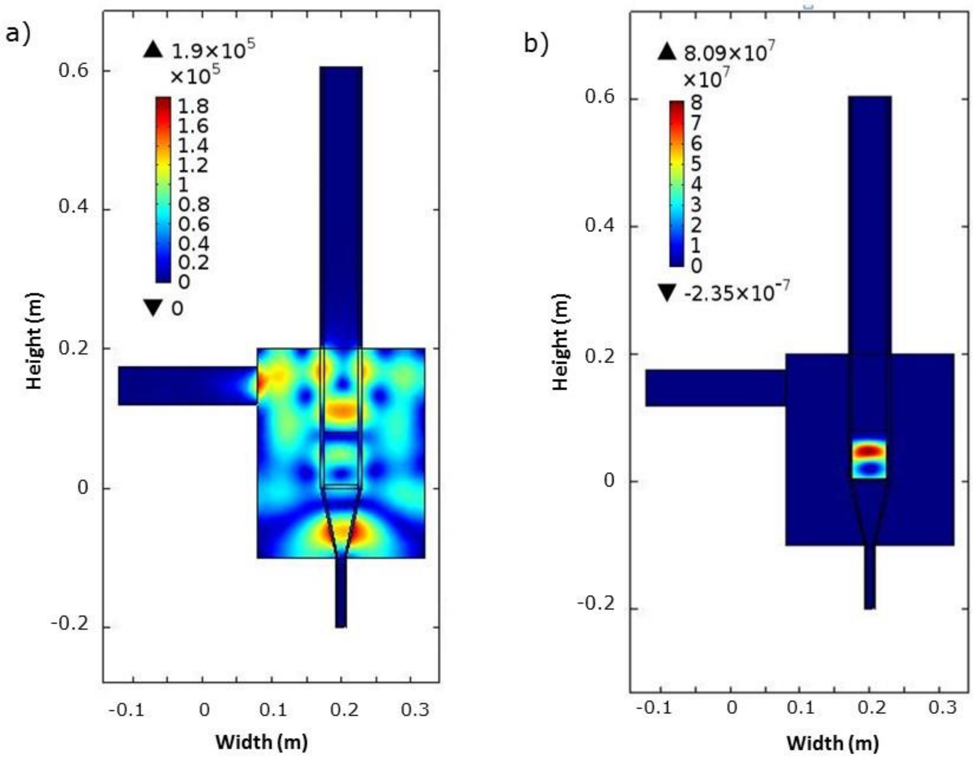

Figure 16. Spatial distribution showing the solid fraction and velocity inside an auger reactor for conventional pyrolysis [93].

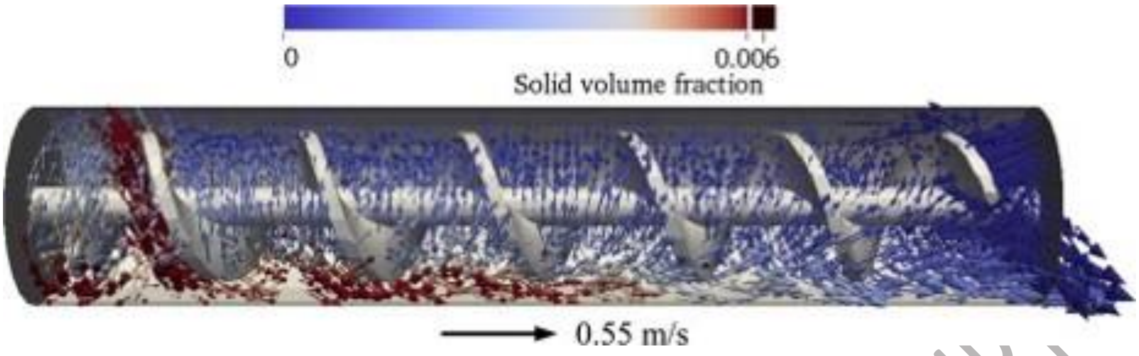

Figure 17. Electromagnetic simulations for microwave pyrolysis of biomass in an extrusion system: (a) Power density across the applicator length (W/m^3); (b) Power density across the biomass depth (W/m^3); and (c) Geometric model including biomass distribution (dark purple) and the twin screws (blue). Dimensions of the rectangular cavity: length, 0.3 m; width, 0.2 m; height, 0.07 m. Only the section between length 2.1 m to 3.0 m has been depicted in Figure 15(a) and 15(b) as the remaining length had negligible power density.