Review Article

Biofuels Production from Biomass by Thermochemical Conversion Technologies

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Agricultural biomass as an energy resource has several environmental and economical advantages and has potential to substantially contribute to present days' fuel demands. Currently, thermochemical processes for agricultural biomass to energy transformation seem promising and feasible. The relative advantage of thermochemical conversion over others is due to higher productivity and compatibility with existing infrastructure facilities. However, the majority of these processes are still under development phase and trying to secure a market share due to various challenges, right from suitable infrastructure, raw material, technical limitations, government policies, and social acceptance. The knowledge at hand suggests that biomass can become a sustainable and major contributor to the current energy demands, if research and development are encouraged in the field of thermochemical conversion for various agricultural biomass types. This paper intends to explore the physical and chemical characteristics of biofuel substitutes of fossil fuels, potential biomass sources, and process parameters for thermochemical conversion.

1. Introduction

Current energy crisis is a product of tremendous amount of pressure on world fossil fuel supply and reserve, which is also implicated with the recent strides of economic developments of countries such as China and India, among others, which are net importers of fossil fuels [1]. The surge in fossil fuel cost ($\cong$ US$150 per barrel) in the recent past clearly indicated that biomass-based fuel options could be more competitive during peak demand periods and a viable mode at other times. The increasing concern over climate change is another important factor that has highlighted the environmental benefits (minimal net greenhouse gas emissions) of the biomass utilization. Most recently, the deep sea crude oil spewing disaster in April 2010 (BP PLC.-Deepwater Horizon oil spill; about 207 million gallons within 3 months period) has undoubtedly confirmed the risks of over exploitation fossil fuel. This incident strengthen the notion of gradual implementation of safe renewable sources to fuel existing fleet of fossil fuel powered domestic, commercial, transportation, and industrial sector. Over the last several decades various researchers have investigated biomethanation, fermentation, and thermochemical pathways for the conversion of biomass to biofuels as energy sources, which is currently getting the attention that was deserved. In general, the biomass could be a complex mixture of organic materials such as carbohydrates (hemicellulose, cellulose, and starch), lignin, fats, and proteins; however, the physiochemical characteristics of biomass vary in discrete fashion with their source. For example, the primary components of the biomass from plant/crop origins are carbohydrates and lignin which can vary with plant type. The source of some biomass includes plant/crop roots, seeds, and seed residue which are rich in starch and fats. On the other hand, many of the biomass types are by products/waste of crops, forest residue, construction and demolition waste, municipal waste, cattle, and human waste. As it was mentioned above, the utilization of biomass as liquid biofuels is a necessary alternative to avoid harmful effects of direct combustion of biomass (as unprocessed/raw solid fuels) which can led to poor air quality, secondary pollution, and undesired health impacts [2].

At present, several biomass thermochemical conversion equipments exist which can transform agricultural biomass into biofuels/bioenergy [3–6]. Nevertheless, there is a great challenge for a farm producer to select the best option due to the infancy of these technologies, intended application (mainly, wood biomass at large scale) as well as a lack of a standard protocol/strategy for agricultural biomass management into bioenergy/biofuels. In brief, a methane digester could be a very attractive solution for handling cattle manure; however, in cold climatic conditions, sensitivity of anaerobic fermentation and secondary waste from digestion process can be huge setbacks [7, 8]. Similarly, land spreading of cattle manure as fertilizer is often limited due to excess nutrient and heavy metals in addition to the agricultural soil [9]. Fermentation of cellulosic biomass for second generation ethanol production itself is a great technical hurdle which requires consistent biomass source, advanced equipments, distribution/collection network, and highly skilled labor. Direct combustion has excellent efficiency for heat utilization but requires advanced technology for the treatment of exhaust gases and secondary waste (e.g., ash) [10–12]. Thermochemical transformation of agricultural biomass is in principle, a highly established technology developed for petroleum and other chemical products. However, the complexity of agricultural biomass and factors (such as moisture, oxygen, sulfur, nitrogen, and metal contents) makes it a challenging task [10, 13–17].

Biofuels are derived from biomass; however, the conversion pathways: biological, physical, chemical, or a combination of processes are pivotal to their type and characteristics. For example, biogas, ethanol, and biodiesel can be produced via microbial/enzymatic fermentations with or without using physical and chemical pretreatment steps [18, 19]. On the other hand, conversion of biomass into bio-oil, biochar, syn-gas, and others requires entirely thermochemical processes, such as torrefaction, carbonization, thermal liquefaction, pyrolysis, and gasification [20–22]). In view of present energy crisis, research and developments in thermochemical processes hold key to a major part of the practical and sustainable energy solution. Therefore, this paper shed light on the recent advancements in the thermochemical production pathways (mainly pyrolysis) for fossil fuel alternative biofuels such as bio-oil, biochar, and combustible gaseous mixtures from forest, agriculture, and municipal residues/wastes. A sustainable farm-practice concept for residue/waste management has also been proposed to generate biofuels from farm manure waste, thereby, serving multiple purposes: reducing the net greenhouse gas emissions, solid waste reduction, carbon sequestration, soil enrichment, and economic benefits among others.

2. Thermochemical Biofuels

Biofuels have distinct physicochemical characteristics depending upon their source/raw material as well as the applied transformation process. Some of the commercially available biofuels are ethanol from corn/cellulosic biomass [23, 24], biodiesel from soybean, canola, *Jatropha*, animal fat, waste cooking oil, and algae [25], biogas from anaerobic digestion of animal manure [8], and thermochemical transformation of various biomass into solid, liquid, and gaseous fuels [20]. With respect to other renewable energy sources, thermochemical biofuels are relatively newer from commercial point of view; however, they are getting much more attention lately as these biofuels offer several technical and strategic advantages [26]. For example, the industrial infrastructure to supply thermochemical transformation equipments for innovative technologies is highly developed. Moreover, the biofuels can be produced from virtually all sorts of available biomass in reasonable timeframe without significant modification in the overall process. On the other hand, despite having certain benefits, bioconversion using microbes and enzymes lacks robustness at industrial scale due to complexity and variable nature of biomass as feedstock both in terms of availability of quality and quantity. In addition, thermochemical transformation is virtually independent of environmental conditions for production purposes. Therefore, it would be imperative to understand the properties of thermochemical biofuels to assess their future market potential.

2.1. Bio-Oil. Bio-oil is a term used for liquid fuel product of biomass pyrolysis. The color varies from light brownish yellow to dark brown for various fractions during condensation phases with pungent-smoky odor and acidic pH. Bio-oils are complex mixtures of chemical compounds that are obtained from the decomposition of cellulose, hemicelluloses, lignin along with other organic entities [35]. The single most abundant compound in any bio-oil would be water (up to 40% w/w) which is crucial in determining the energetic value as well as physiochemical properties such as pH, viscosity, and phase separation. Bio-oils can also contain some fine solid particles (aerosols). The fuel characteristics of bio-oils are in principle due to hundreds of organic compounds that belong to sugars, organic acids, alcohols, aldehydes, ketones, phenols, esters, ethers, furans, nitrogen and sulfur compounds, and multifunctional compounds [44]. Evidently, the molecular weights of bio-oil compounds vary from 18 (water) to 5000 or even more for partially degraded pyrolytic lignins. The average molecular weight for different fractions of bio-oils can vary in the range of 370–1000 g/mol. For now, more than 300 organic compounds have been reported in various bio-oils from different source. Table 2 represents physicochemical characteristics of bio-oils obtained from different pyrolysis processes/conditions studied by various researchers. These properties can vary substantially with respect to biomass source. In order to facilitate analysis and quantification of compounds, fractionation chromatography of bio-oils is used to separate bio-oils into different groups of chemical compounds [45, 46]. However, complete chemical characterization of bio-oils is practically not feasible due to the formation of pyrolytic lignins, which are randomly broken at different lengths of the polymeric chain [17]. The structural and compositional complexity of lignin could be assessed by its pyrolysis products such as guaiacol from coniferous wood and guaiacol and pyrogallol dimethyl ether from deciduous woods [47]. Despite having a much higher methoxyl content than wood, lignin results in higher yields

of charcoal and tar. [21, 29, 33, 48, 49]. It is postulated that pyrolysis reaction produces the most substituted phenols on a selective basis. In fact, the syringyl-propan units are linked to the lignin skeleton to a lesser extend with respect to the less substituted: guaiacyl-propane and phenyl-propane [50]. Thus, lignin derivatives are major constituents of any bio-oil and contribute to its complexity and distinct characteristics for different biomass source.

Bio-oils are the most preferred pyrolysis fuel types for transportation and storage purposes for obvious reasons such as compatibility with many existing equipments, pumping, and safety. However, in most cases it may not be suitable to use it directly and would require refining and further processing steps similar to fossil crude oil in petroleum refineries. The aging or stability of bio-oils is also of great concern as once pyrolysis is over, bio-oils start degrading or undergo further reactions among different chemical species albeit at much slower pace [6]. Furthermore, bio-oils from specific wood biomass are used as starting raw materials for the production of high value food flavoring agents, likewise, bio-oils from waste/renewable biomass could be refined by modified processes by the existing petroleum refineries for the production of commercial grade fuels and some high-value chemicals [44].

2.2. Biochar. Biochar is a pyrolysis byproduct along with bio-oil and flue gases. In recent times, biochar is less preferred over bio-oil as fuel source due to handling, incompatibility with transportation sector (automobile engines), storage, and secondary pollutants issues (higher ash content) [37–39]. This was also reflected in the literature citation for the present review, where much more research studies were aimed at the production of bio-oil than biochar (Tables 1 and 2). Nevertheless, except for incompatibility as biofuels for transportation sector, biochar has several merits, which make it an important byproduct of pyrolysis from the economic feasibility point of view. The usefulness of biochar in agricultural sector as well as in general has been the focus of several recent studies [20, 26, 34, 51–54]. Therefore, it is quite essential to explore the optimal and sustainable utilization of biochar in order to achieve environmental and economic goals of pyrolysis process. Gaunt and Lehmann [54], have reported energy balance and emission reduction potential of biochar in soil amendment application. The authors carried out the study based on their previous findings about net reduction in methane (CH_4) and nitrous oxide (N_2O) of soil amended with biochar [55]. The potential applications of biochar include soil enhancer, bulking agent for composting, activated carbon, remediation of water and soil, energy, and carbon sequestration [26, 51, 52, 54]. It is an established fact that biochar is very stable compared to raw biomass and has positive effects on overall plant growth. The very basic physical and chemical characteristics of biochar such as pH, porosity, affinity for metal adsorption, slow release of nutrients such as phosphorous and nitrogen, among others help in improvement of soil quality (Table 3). This can potentially reduce the requirements of conventional dosage of fertilizers, thereby, improving the economic output as well as abate the chances of nutrient runoff, erosion, and

Table 1: Advantages of thermochemical conversion of biomass over biological/biochemical process.

Thermochemical	Biological/biochemical
(1) Effectively applied to almost any biomass feedstock	Involves the use of microbes, enzymes, and/or chemicals to utilize the limited range of biomass
(2) Relatively higher productivity (production per unit time) due to completely chemical nature of reaction	Productivity is limited due to biological conversion. Increase would require higher capital investment such as bigger reactor
(3) Multiple high-value products possible using fractional separation of products	Normally, limited to one or few products and would require additional microbial culture, enzymes for more products
(4) Independent of climate conditions, operates at much higher temperature range, therefore, effect of ambient temperature will be minimal	Mostly susceptible to ambient temperature, and so forth such as anaerobic digester, sunlight for algal ponds
(5) Mostly complete utilization of the waste/biomass	Production of secondary wastes such as biomass sludge

greenhouse gas release. The above views and facts are based on the results of several authors [54, 55] which reported a reduction of 50–100% of CH_4 and N_2O as well as increase in efficiency of fertilizer utilization in soil amended with biochar. The use of biochar as reducer in metallurgical industry, particularly in Brazil, has also expanded the potential market of biochar [33]. Another important advantage about the biochar application as soil amendment product is the amount of carbon sequestered. Research studies have shown the stability of biochar obtained from different biomass to be between 100–10000 years or even more [56]. Therefore, the potential of generation of revenue from carbon emissions trading for biochar production can further reduce the overall operational costs of a pyrolysis plant [54]. Our own experience with an experimental pyrolysis reactor under development has proved that it is relatively easier to produce biochar at desired yield with respect to bio-oil. Therefore, the production technology for biochar is no hurdle, but dissemination of knowledge about practical utilization of biochar in agriculture and formulation of regulatory standards of its use and C emissions trading values remains to be established.

2.3. Noncondensable Pyrolysis Gas. The gaseous fraction of pyrolysis vapor is, in general, referred to as pyrolysis gas, flue gas, and noncondensable pyrolysis gas. It is composed of various gases such as CO_2, CO, NO_X, SO_X, H_2S, H_2, aldehydes, ketones, volatile carboxylic acids, and gaseous hydrocarbons. However, pyrolysis gases can also be composed of volatile compounds in the absence of efficient condensation system. The major gas components of pyrolysis are CO_2 and CO, which have been reported by several researchers for different

TABLE 2: Physicochemical characteristics of bio-oils obtained by different processes/biomass types.

Study	Biomass source	Pyrolysis temperature (°C)	Bio-oil yield (wt%)	Moisture content (wt%)	pH	Specific gravity @°C	C	H	N	O	Ash (wt%)	Calorific value (MJ/kg)	Viscosity (cP) @ temperature (°C)	Solids (wt%)	Distillation residue (wt%)
Salehi et al., [6]	Sawdust of mixture of woods	500	33–45	39	1.85	1.05@15	30.72	6.67	1.07	61.54	—	10.93	9.84@25	—	—
Czernik and Bridgwater, [27]	Wood	—	—	15–30	2.5	1.20@15	54–58	5.5–7.0	0–0.2	35–40	0–0.2	16–19	40–100@50	0.2–1.0	up to 50
Ates and Isikdag, [28]	Oat straw	600	20.3	—	—	—	65.0	6.9	1.3	26.9	—	32.74*	—	—	—
	Wheat straw		19.1	—	—	—	71.1	8.5	0.5	19.8	—	27.09*	—	—	—
Azeez et al., [29]	Beech	470	62.7	22.2	2.5	—	41.4	7.1	0.2	51.2	—	16.9	15.2**@40	0.2	15#
	Spruce		62.7	22	2.8	—	42.3	7.2	0.2	50.3	—	17.2	14.8**@40	0.1	15.4#
	Iroko		50.6	32.3	2.9	—	38.2	7.5	0.3	54	—	15.9	—	0.2	14.1#
	Albizia		54.7	25.1	2.9	—	41.9	7.4	0.6	50.1	—	17.4	57.1**@40	0.2	12.2#
	Corn cob		56.7	32.2	3	—	38.1	8	0.7	53.2	—	15.8	6.7**@40	0.1	8.5#
Bhattacharya et al., [30]	Pine : polystyrene (50 : 50 w/w)	525	64.9	9.47	2.82	0.98@15	66.27	6.72	<0.5	7.02	—	28.42*	28.94**@—	—	—
	Pine : high-density polyethylene (50 : 50 w/w)	450	38.9	10.65	3.21	1.24@15	74.38	9.11	<0.5	6.33	—	27.68*	—	—	—
	Pine : polypropylene (50 : 50 w/w)	450	46	5.44	3.02	1.09@15	79.7	10.64	<0.5	9.5	—	36.94*	23.6**@—	—	—
	Pine wood	450	50.10	13	3.1	1.19@15	57.2	7	<0.09	32.2	—	—	80.7**@—	—	—
Boateng et al., [31]	Switchgrass	480	60.71	23.02	—	1.25@15	40.78	6.98	0.33	47.25	0.011	16.02	22.14**@40	—	—
Fonts et al., [32]	Wastewater sludge	550	~50	27.2–46.6	—	0.972–0.975@15	—	—	—	—	—	30.60–32.09*	—	0.07–0.12	—
García-Pérez et al., [33]	Softwood	500	45.0–53.9	—	3.0	1.188@20	62.59	7.02	1.05	29.02	0.25	27.9*	62**@50	—	—
He et al., [34]	Swine manure	350	76.2	—	—	—	77.9	9.4	4.6	7.0	1.0	38.63*	—	—	—
Hilten et al., [35]	Pine wood pellets	450	57.7	10.0	2.48	1.18@15	64.9	7.1	0.2	27.8	—	27.6*	300**@40	—	—
Miao and Wu, [36]	Microalgae	450	57.2	—	—	0.92	76.22	11.61	0.93	11.24	—	41*	20@40	—	—
Mullen et al., [37]	Corn cob	500	61.0	—	—	—	55.14	7.56	0.56	36.9	0.08	19.5*	—	—	—
	Corn stover		61.6	—	—	—	53.97	6.92	1.18	37.94	0.09	22.1*	—	—	—

TABLE 2: Continued.

Study	Biomass source	Pyrolysis temperature (°C)	Bio-oil yield (wt%)	Moisture content (wt%)	pH	Specific gravity @°C	C	H	N	O	Ash (wt%)	Calorific value (MJ/kg)	Viscosity (cP) @ temperature (°C)	Solids (wt%)	Distillation residue (wt%)
Mullen et al., [38]	Whole barley straw	~500	42–50	26.7	2.4	—	50.78	3.2	1.37	44.42	—	24.2*	23.5**@40	—	—
	Whole barley hulls			13.8	2.4	—	54.73	5.32	1.79	38.49	—	24.1*	102**@40	—	—
	Distiller's dried grains with solubles			18.7	6.5	—	74.02	8.92	5.05	6.24	—	32.9*	277**@40	—	—
Oasmaa et al., [3]	*Pinus sylvestris*	480–520	72.7	23.9	2.7	1.206	40.6	7.6	<0.1	51.7	0.03	20.1	17	0.01	—
	Forest residue (brown)		57.9	26.7	3.2	1.194	41.4	7.4	0.3	50.9	0.3	20.9	17	0.17	—
	Forest residue (green)		63.7	25.5	—	1.21	41.2	8	0.3	50.5	0.1	20.4	24	0.09	—
	Eucalyptusgrandis		70.8	20.6	2.2	1.229	42.3	7.5	0.1	50.1	0.03	19.7	23	0.09	—
	Barley straw		52.0	51.1	3.7	—	26.5	9	0.9	62.7	—	18.6	—	0.43	—
	Timothy hay		52.5	39.3	3.4	1.15	32.1	8.5	0.6	58.7	0.004	18.4	5	0.01	—
	Reed canary grass		75.0	27.4	3.6	—	39.3	7.7	0.6	51.8	—	19.7	—	0.15	—
Uzun et al., [39]	Olive-oil residue	550	—	—	—	—	69.52	8.62	1.76	21.24	—	32.13	—	—	—
Xiu et al., [40, 41]	Swine manure	500	24.2	2.37	—	—	72.58	9.76	4.47	13.19	0.13	36.05*	843@50	—	—
Yin et al., [42]	Cattle manure	310	48.76	—	—	—	73.72	8.13	1.39	16.76	—	35.53*	—	—	—
Zhang et al., [43]	Corn cob	550 (without catalyst)	56.9	—	2.8	1.18	51.94	6.96	0.82	40.28	—	18.8*	—	0.30	—
	Corn cob	550 (with catalyst)	~51.0	—	5.2	0.95	74.1	9.33	1.88	14.69	—	34.6*	—	0.20	—

— Not available.
* High heating value (HHV).
** Kinematic viscosity, cST.
# Lignin content.

TABLE 3: Characteristics of biochar produced by different processes/biomass types.

Study	Biomass source	Moisture (wt%)	C	H	N	O	Ash (wt%)	Calorific value (MJ/kg)	Temperature (°C)	Yield (wt%)
Boateng et al., [31]	Switchgrass	3.78	60.71	3.99	0.75	8.7	25.85	19.37	500	12.9
Mullen et al., [38]	Wheat straw	—	71.10	2.99	0.29	25.62	—	28.05*	500	~35–40
Abdullah and Wu, [57]	Mallee wood	4.6	60.3	5.3	0.18	34.14	0.70	22*	300	~56
Acikgoz et al., [58]	Linseed	—	61.63	2.57	4.08	31.73	—	24.12*	550	~15–20
Cao and Harris, [51]	Dairy manure	—	25.2	—	2.22	—	~55	—	350	~20–35
Mohan et al., [59]	Oak wood	3.17	82.83	2.70	0.31	8.05	2.92	31.03*	400	17–27
	Pine wood	2.69	83.47	2.99	0.27	8.25	2.30	31.68*		
	Oak bark	1.56	71.25	2.63	0.46	12.99	11.09	25.75*	450	
	Pine bark	2.31	68.25	2.51	0.34	10.80	15.75	25.25*		
Mullen et al., [37, 38]	Corn cobs	—	77.60	3.05	0.85	5.11	13.34	30.0*	500	18.9
	Corn stover	—	57.26	2.86	1.47	5.45	32.78	21.0*		17.0
Mulligan et al., [60]	Wheat straw	4.6	73.6	2.34	2.58	8.0	13.3	28.1*	500	32
	Mallee wood	4.6	78.7	2.48	1.18	8.7	8.9	29.9*		36
Salehi et al., [6]	Mixed sawdust	—	83.11	3.69	0.18	13.02	—	30.77*	500	20–27
Uzun et al., [39]	Olive oil residue	—	54.98	2.76	0.53	41.73	13.81	15.06*	400	—
		—	56.21	2.16	0.32	41.31	16.77	14.27*	500	—
		—	59.01	1.61	—	39.38	20.17	15.18*	550	—
		—	61.16	1.03	—	37.81	21.60	15.36*	700	—
Yang et al., [61]	Palm oil waste	—	76.81	1.46	2.32	11.47		—	600	28.57

* High heating value (HHV).

biomass types [62–64]. Pyrolysis gases have relatively lower average calorific value (an approximate estimation based on gas composition and concentration data from few studies in this paper is around 1.3 MJ/kg, [65]), therefore, almost all pyrolysis processes involve utilization of pyrolysis gases to contribute to heat the pyrolysis reaction [12, 44]. The presence of H_2O in pyrolysis gas is governed by the cleavage of aliphatic hydroxyl groups, which is not easily possible to avoid during pyrolysis, and it also affects the overall fuel quality of the pyrolysis products [62]. Tihay and Gilard [62], also detected the possibilities of formation of CO_2 via cleavage and reforming of functional groups of carboxyl (C=O). The production of CO was proposed from the cleavage of carbonyl groups (C=O) and of the bonds C–O, C–O–C, and C–C, and the production of CH_4 was mainly caused by the cleavage of methoxyl groups (–O–CH_3) and the break of methylene [62]. In general, pyrolysis gas is not a desired product; nevertheless, it is inevitable during pyrolysis process. The pyrolysis gas can be used to directly or indirectly preheat the biomass followed by burning via burner to generate heat requirements for pyrolysis process. The burning of pyrolysis gases poses a burden of treatment of combustion products which cannot be directly introduced into the environment. The presence of potential pollutant gases NO_X, SO_X, H_2S, and aerosols in pyrolysis gases depends upon the biomass source such as animal waste, agricultural waste, and municipal waste. Nevertheless, there are many options for the treatment and purification of the pyrolysis gases such as electrostatic precipitator, NO_X scrubbers, adsorption systems based on activated carbon for volatile organic compounds, flares, flue gas desulfurization systems for SO_X, and biofilters [66].

3. Feedstock

In Canada only, there are about 6 004 944, and 8 700 000 dry tonnes/year production of municipal biosolids (organics), and forest residue (wood) [67]. Canada is also a global figure in biomass pellets production and exports about 10% of the 10 million tonnes per year of world demand for green energy market. In addition, cereal straw, corn stover, and flax straw are significant contributor to agricultural biomass residue as they occupy more than 85% of 36.4 million hectares of cropland in Canada [67]. Multiple options for natural resources for energy such as hydroelectricity, biomass, fossil fuels, tidal, wind, and solar enable Canada as a net exporter of energy and energy sources. However, in order to mitigate greenhouse gases and climate change effects and enhance

economic output, innovative biomass/waste utilization skills for energy and valuable products should be universally applied.

3.1. Agricultural Biomass. The greenhouse gas emissions coming from the agricultural sector accounted for 8.6%, which is based upon the use of either fossil fuels or their products (e.g., fertilizers) in agriculture. The estimated potential of agricultural residues for energy production is overwhelming, which is 1 and 9 billion barrels, respectively, for USA and world; nevertheless, a pragmatic utilization of agricultural residue for bioenergy should be carried out [68, 69]. In the literature, there are many studies on agricultural residues such as olive seed residue, hazelnut bagasse, corncobs, tea waste, sugar cane bagasse, and cotton [11, 65, 70]. It is essential to understand that most of the agricultural residues (such as crop residues) can be transformed to other valuable products. Even without any transformation, simple tillage practice of crop practice is very important to conserve soil physiochemcial and microbial characteristics. Intense animal farming puts substantial load on animal feed supply, which is dependent on crop/crop residue production. Therefore, if a required fraction of the animal waste is not returned to the cropland, the overall approach could not be sustainable even in case of biofuels or added value products. In this regard, production of bio-oil and biochar from pyrolysis of animal waste or agricultural residue could be an interesting approach since application of biochar (as soil enhancer/conditioner) to the cropland has great potential [51, 52, 54, 56, 57]. Therefore, agricultural biomass has a good potential for the sustainable production of biofuels and valuable products via pyrolysis.

3.2. Municipal Waste. Municipal waste can consist of organic solids of up to 65% or more depending upon urban waste management practices (e.g., source separation) and socioeconomic status. Utilization of the bioorganic part of the municipal waste as biomass feedstock for pyrolysis can be a rational approach, if it is integrated to the electricity generation using heavy oil-based generators. In this case, the biochar and pyrolysis gas can be entirely utilized to provide heat requirements for pyrolysis process and the ash generated could be diverted to manufacture construction materials. In the literature, there are several reported studies on municipal solids at different stages (without and after biological treatments) [32, 71–75]. However, municipal solids have many conventional and newer treatment methods (biological, incineration, anaerobic digestion, and landfill) and are regarded as priority pollutants by municipalities. Therefore, economic aspects of the disposal and management of municipal solids have not been a major concern until lately. Nowadays, most municipalities are looking forward for biomass-to-energy conversion technologies in order to improve their treatment efficiency, reduce greenhouse gases emission and economic viability. In the present scenario, pyrolysis technologies of municipal solids to energy products could be a feasible option. However, the mass scale initiatives are taken based on local conditions of quality and quantity of municipal solids, existing electricity cost, conventional methods of disposal of secondary wastes (landfill or composting).

3.3. Forest Residue. The initiatives of application of pyrolysis technologies to biomass were mainly taken for forestry residue and sawdust from timber industry. Therefore, nearly all existing demo- or commercial scale biomass pyrolysis plants are designed for wood residues (Dynamotive Corp., Ensyn Inc., BTG-BTL Inc., RTI Inc., and many others). The most appealing features of forest residue for pyrolysis process are the sustainable supply network on large scale basis, and suitability of the feedstock (lower moisture, ash, metals, nitrogen, and sulfur contents). Forest residue could be a reliable and sustainable biomass feedstock for pyrolysis plants in forest biomass countries like Canada, USA, and others with developed forest industry sector. However, in order to compete with fossil fuels the forest residue based on pyrolysis plants should be strategically placed to minimize cost of forest residue transportation. Analogous to fossil fuels, many mid to small scale pyrolysis units can be placed near to forest region as in the case of land-based or offshore oil rigs. The bio-oils produced by these multiple units can then be converged to a commercial scale bio-oil refinery for value addition or electricity generation plant depending upon the economics, similar to transportation of fossil fuels to petroleum refineries. In fact, some of the large scale pyrolysis plants in Europe are under experimental or demonstration phase for the evaluation of this apparently promising approach [12].

4. Thermochemical Processes

4.1. Fast/Flash Pyrolysis. In recent times, pyrolysis process is getting unprecedented attention from forestry, municipalities, and agricultural sector due to its potential for conversion of virtually all types of biomass into commercially viable biofuels and valuable chemical feedstocks for industrial sector. The concept of pyrolysis is not a novel approach as such, which is already in use for the production of several valuable chemical feedstocks. Nevertheless, it is a relatively recent process for the production of liquid fuels and electricity. However, in principle, any type of high temperature heating of organic matter in the absence or substantial deficiency of oxygen can be defined as some type of pyrolysis process. The term "biomass pyrolysis" is normally associated with the processes involving bio-oils and chemical feedstock production. The terms, torrefaction/carbonization, thermal liquefaction, and gasification can be separately used based upon operational parameters and intended applications. These processes are also mentioned briefly to provide an overview (Figure 1).

The term fast/flash pyrolysis is used for pyrolysis processes with very short residence time of intense thermal treatment, usually, it lasts from 0.5–3 s at 400–600°C [17]. The shorter time of heat exposure of the organic matter (e.g., biomass) in fast/flash pyrolysis process results in increased significance of heat and mass transfer, and phase transition along with chemical reaction kinetics [12]. Long residence
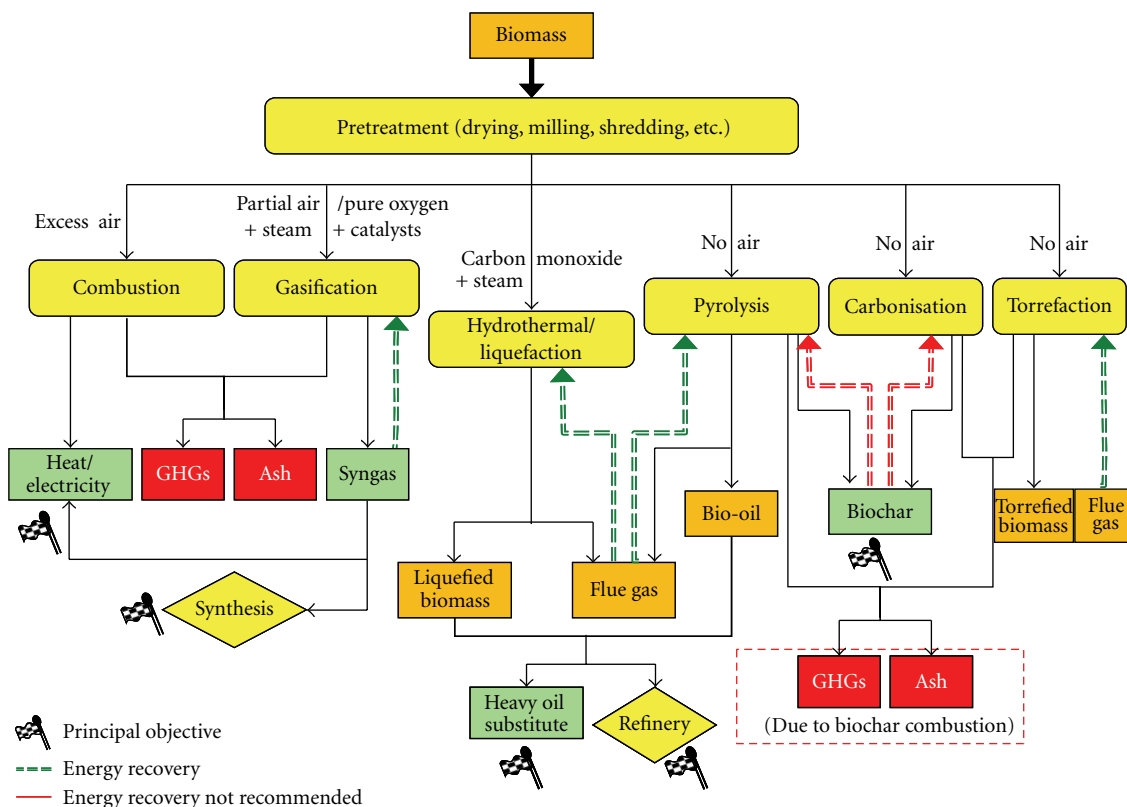
Figure 1: Biomass thermochemical conversion pathways.

times (few minutes to hours) and lower temperature range (200–350°C) favor charcoal formation. In principle, fluidized bed reactors use smaller particle size and high temperature to achieve very fast heat transfer, thereby, minimizing char formation. Interestingly, the low thermal conductivity of biomass particles is very well exploited in ablative reactors where biomass pellets are pressed against heated surface, forming pyrolysis vapor as well as exposing unaffected inner surface. Some of the prerequisites for fast pyrolysis are dry biomass (≤10% moisture), small particle size (≤3 mm), short residence times, moderate-to-high temperatures, and rapid quenching of pyrolyzed vapor. The lack of predictive kinetic constants for fast pyrolysis is due to its unsteady state nature as the biomass complexity requires multistage thermal decomposition with production of substantial quantities of highly unstable compounds (at process temperatures). All these factors have great impact on the design of a fast pyrolysis system which should rapidly heat biomass to desired temperature as well as quickly quench down the products.

4.2. Thermal Liquefaction. Thermal liquefaction can often be confused with pyrolysis in simplified comparisons [47]. The two processes differ in operating parameters, requirement of catalyst, and final products. Liquefaction produces mainly liquid and some amounts of gaseous components at temperature and pressure ranges of 250–350°C and 700–3000 psi, respectively, in the presence of alkali metal salts

as catalyst. The liquefaction may also require supplemental CO and H_2 as reactants to facilitate the overall process. The mechanisms of liquefaction reactions lack sufficient description about role of catalysts. In the past, some researchers have proposed possible mechanisms for Na_2CO_3 and K_2CO_3 for biomass liquefaction [76–78]. The catalysts hydrolyse the cellulose, hemicelluloses, and lignin macromolecules into smaller micellar-like fragments, which are further degraded to smaller compounds via dehydration, dehydrogenation, deoxygenation, and decarboxylation reactions. In comparison to torrefaction/carbonization, thermal liquefaction can provide liquid fuels in line with petroleum products along with several high value chemicals; however, recent trends in biomass thermochemical conversion, liquefaction, could not be successful at commercial scale. The possible factors that limit the liquefaction commercialization could be the lower overall yield of oil (between 20–55% w/w) compared to contemporary options like pyrolysis (discussed later), inferior oil quality (heavy tar like liquid), stricter operational parameters (higher reaction temperature and pressure), and requirements of catalysts and/or other reactants (CO, propanol, butanol, and glycerine).

4.3. Carbonization and Torrefaction. Carbonization and torrefaction are closely related processes (**Figure 2**). The former is mainly intended for biochar production, whereas, the latter is a thermal treatment to convert biomass into more efficient
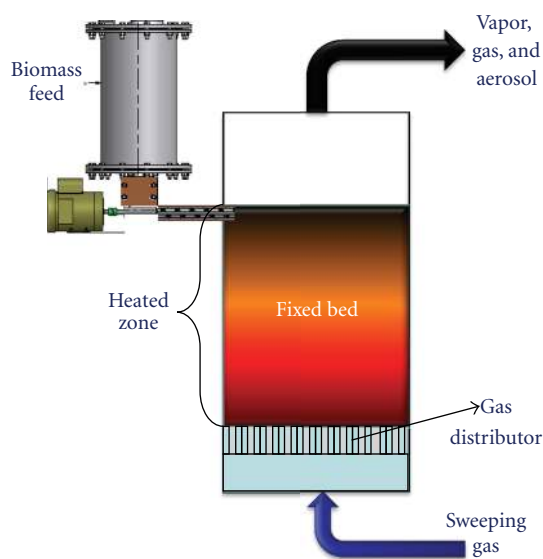
Figure 2: Fixed bed reactor concept for biomass pyrolysis.

form of energy source with less moisture and high fixed carbon, production of chemical feedstocks and to reduce the associated transportation costs.

For carbonization, the biomass is thermochemically treated in the temperature range between 200 to 315°C in the absence of oxygen [79]. Carbonization is accomplished by complete conversion of biomass into biochar. Thus, the product gains much higher energy density than the raw biomass, which lowers the transportation cost of the carbonized biomass.

In the case of torrefaction, there is partial decomposition of the biomass (especially the hemicellulose), giving off various types of volatiles resulting in brittle, dried and more volatile free solid product.

Moreover, carbonized/torrefied biomass has favorable characteristics such as, hydrophobic nature, similar or closely related properties as coal, easy to crush, grind or pulverize. The end-products comprise condensable gases such as water vapor, formic acid, acetic acid, furfural, methanol, lactic acid, phenol, and other oxygenates. Noncondensable gases such as carbon dioxide, carbon monoxide and small amounts of hydrogen and methane are also obtained. Thus, carbonization and torrefaction processes are used for the conversion of biomass into more efficient forms of energy source and to reduce the associated transportation costs. Nevertheless, it is not in competition with petroleum fuels in transport sector.

4.4. Gasification. Biomass gasification has also received much attention in recent times [2, 7, 10, 12, 20, 24, 71, 80–83]. The biomass is converted to simplified products, CO and H_2, in the optimized concentrations of oxygen and H_2O (steam reforming) at temperatures ≥800°C which is completely distinct from gasification via anaerobic digestion. The final products are syngas (CO and H_2 mixture), CO_2, NO_x, SO_x, and ash/metal slag (quantity will depend upon

the type of the waste: municipal, agricultural, or wood biomass). Syngas has multiple applications such as fuel cells, synthetic fuel, and chemical feedstocks. Thus, technically gasification is an excellent method of extracting bioenergy free from N, P, S, Cl and metals contamination from diverse biomass types without further treatment/upgrading. Many biomass gasification processes are under development or at trial stage for biofuels and electricity generation, and waste disposal such as Enerkem, Thermoselect, GE Energy-Nexterra, Choren, among many others. However, positive electricity efficiency, biomass drying and grinding, oxygen input, reactor cleaning and maintenance, and economic feasibility are some major challenges for biomass gasification which are at research, pilot and demo scales.

5. Fast/Flash Pyrolysis Reactors

There are several types of fast/flash pyrolysis reactors both at developmental and commercial scale [12, 17, 44, 84, 85]. Different reactor configurations were inspired by the requirements such as the high heat transfer rates, separation of solids and gas phase, rapid condensation, and energy autonomy (Table 4). In the past, there are some excellent reviews about various pyrolysis reactors [12, 44]. Nevertheless, the highly dynamic research environment of biomass fast pyrolysis required timely update about developments in fast pyrolysis reactors. In this paper, major fast pyrolysis reactors are discussed in the following with their most recent information.

5.1. Fixed Bed. Fixed bed fast pyrolysis of biomass has been mentioned by many researchers [5, 6, 28, 57, 58, 80, 86–88]. However, in most of the cases the quantity of biomass taken for pyrolysis was in the range of few grams (g) and were aimed at analytical and laboratory scale investigation. A schematic diagram of a fixed bed reactor is shown in Figure 2. Schröder [88], used 2 kg of biomass of ~10 mm particle size and examined the validity of the fixed bed model. The author explained the importance of studying the chemical kinetics using larger particle size in comparison to common TGA analysis, where small sample of fine particles is used, therefore, the effect of transport phenomena becomes insignificant. Acikgoz et al. [58], investigated the pyrolysis of linseed seed samples in a well-swept resistively heated fixed bed tubular reactor (0.8 cm i.d., and 90 cm long), consisting of steel wool as fixed bed and constructed from 310 stainless steel. The pyrolysis operation was conducted by putting 2 g of air-dried sample of average particle size between 0.6–1.8 mm onto the fixed bed. A sweep gas velocity of 100 mL min^{-1} was maintained with heating rate that was kept as high as 300°C min^{-1}. Although the bio-oil yields were comparable to prior literature, no possible future scale-up of the reactor was mentioned. Likewise, fixed bed pyrolysis reactors have been used for evaluation of operating parameters such as temperature, heating rate, particle size, and cooling methods for different types of biomass, but no practical or commercial applications have been developed to the best of our knowledge. The possible reasons for lack of commercial scale fixed bed pyrolysis reactors could

TABLE 4: Comparison of various biomass pyrolysis reactors based on overall performance and efficiency.

Pyrolyzer	Status (units)	Bio-oil yield (wt%)	Operational complexity	Particle size	Biomass variability	Scale-up	Inert gas flow rate
Fixed bed	Pilot (single), lab (multiple)	75	Medium	Large	High	Hard	Low
Fluidized bed	Demo (multiple), lab (multiple)	75	Medium	Small	Low	Easy	High
Recirculating bed	Pilot (multiple), lab (multiple)	75	High	Medium	Low	Hard	High
Rotating Cone	Demo (single)	70	Medium	Medium	High	Medium	Low
Ablative	Pilot (single), lab (multiple)	75	High	Large	High	Hard	Low
Screw/auger reactor	Pilot (multiple), lab (multiple)	70	Low	Medium	High	Easy	Low
Vacuum	Pilot (single), lab (few)	60	High	Large	Medium	Hard	Low

be maintenance problems such as clogging of reactor bed with char and tar compounds, and increased resistance for sweeping gas flow, which could be easily resolved in the other reactor types mentioned in the following.

5.2. Fluidized Bed. Fluidized bed pyrolysis reactors are the most documented and commercially available reactor types amongst all pyrolyzers [29, 31, 32, 37, 38, 43, 89, 90]. More precisely, these are also known as bubbling fluidized bed reactors, where a hydrodynamically stable bed of smaller size biomass particles (0.5–2 mm) is maintained using an inert fluidizing gas such as nitrogen (Figure 3). In order to provide better heat transfer, entrapment of char particles, and temperature control, sand/carrier material is also entrained along with fluidizing gas to increase attrition/abrasion of biomass particles. The lack of mechanical parts allows easy scale up and maintenance, but fluidizing high volumes of biomass and carriers (e.g., sand) requires relatively higher energy and considerable part of capital investment in gas blowers. Fluidized bed reactor concept is well understood; therefore, it was possible to design and develop pyrolyzers at pilot and commercial scale as many crucial heat and mass transfer models during particle fluidization from prior studies were available. The fluidized bed reactor design enables minimizing catalytic cracking of pyrolysis vapor by char via quick separation of char particles using cyclones. Several fluidized bed pyrolyzers are operating at high quality bio-oil yields around 70–75% w/w with trouble-free operation and minimal maintenance [44] while, many other types of pyrolyzers have many operational as well as product quality challenges (discussed later). Therefore, the relatively higher energy requirements and considerable part of capital investment in gas blowers are easily disregarded by the investors. Furthermore, fluidized bed pyrolyzers have some established technologies in the market, such as RTP (Ensyn Inc.), and RTI (Dynamotive Corp.) along with many small scale reactors. However, increasing competition from other biofuels, and fossil crude oil, other potential concepts for fast
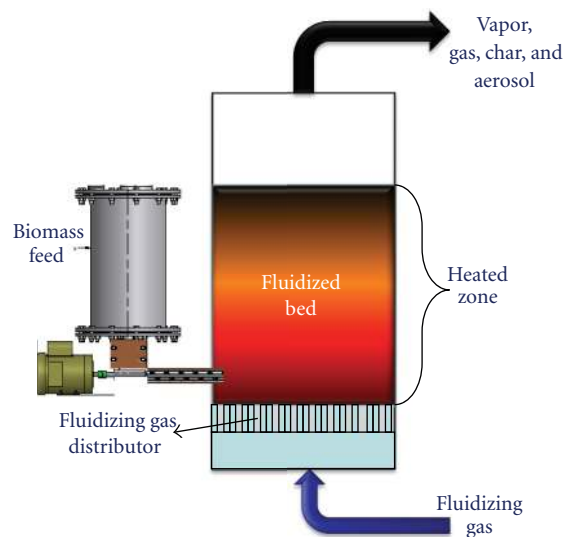

FIGURE 3: Generalized diagram for fluidized bed reactors for biomass pyrolysis.

pyrolysis involving lesser energy requirement and ability to use waste biomass are also getting increased attention.

5.3. Recirculating Fluidized Bed. Recirculating fluidized bed reactors are also referred as circulating fluidized bed or transport bed reactors which are more complex version of bubbling fluidized bed reactors (Figure 4). Similar to bubbling fluidized bed, this pyrolyzer type is also well understood and substantial literature data is available on its operation including biomass pyrolysis [31, 32, 37, 89]. In contrast to bubbling fluidized bed reactors, these pyrolyzers have lower heat transfer but better char attrition due to higher gas velocities via recirculation/reflux. The bio-oil yield of recirculating bed reactors is also similar to fluidized bed reactors but reheating of sand/carrier particles requires
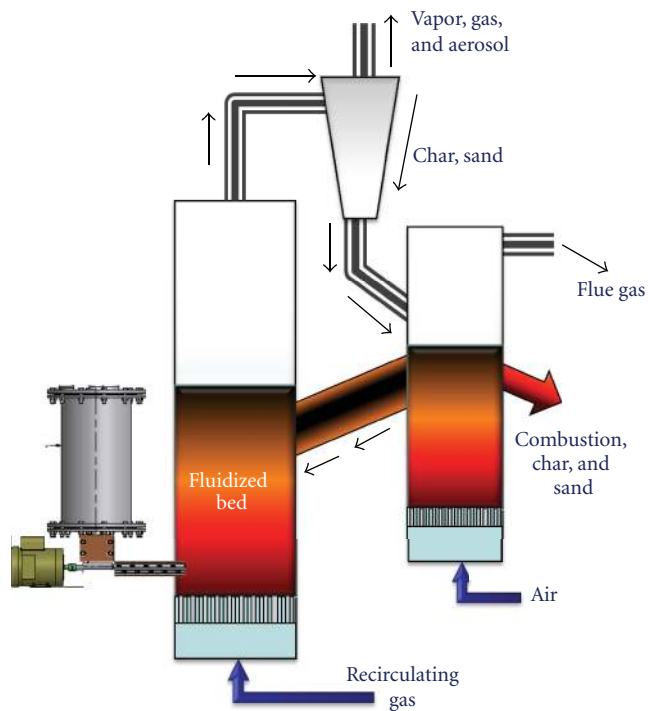
Figure 4: Schematic of recirculating fluidized bed pyrolyzer.

Figure 5: Rotating cone reactor.

combustion of entrapped char which may lead to ash build up in the circulating bed. The major advantages of this reactor type are energetically self-sustainable pyrolysis which is easy, and high throughput volumes of biomass are possible due to high gas velocities. On the other hand, ash buildup can cause catalytic cracking of pyrolysis vapor and lead to some decrease in volatile matter in bio-oil, and very high gas velocities require even higher energy requirements for gas blowers. The operation and maintenance of this pyrolyzer type is robust, hence, process energy input concerns are overlooked in most of the cases as it is quite rare to find literature on energy input on such reactors.

5.4. Rotating Cone. Rotating cone pyrolyzer was developed at University of Twente, The Netherlands. This technology was the basis for the BTG-BTL process for the pyrolysis of various biomass types. The advantage of this technology is the absence of inert/carrier gas, thereby, relatively smaller energy requirement. In a rotating cone pyrolyzer, biomass is poured on a high-speed rotating cone along with hot sand in the absence of oxygen (Figure 5). The high speed rotation causes vigorous mixing of biomass and sand particles which in turn lead to fast heat transfer and biomass surface abrasion due to high speed heated sand particles [17, 91]. Thus, fast pyrolysis conditions are achieved with combined efforts of mechanical and fluid mixing. The energy requirements are met by char combustion and the process can be autonomous in terms of energy input for heating the pyrolyzer. Depending upon the biomass source, up to 75% w/w of bio-oil yield has been achieved with an estimated cost of 5 €/GJ which was comparable to diesel
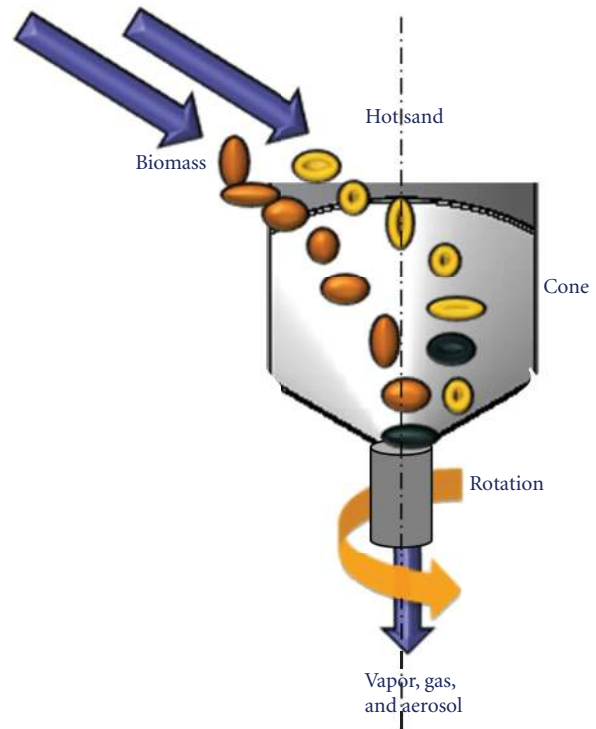
fuel cost of up to 6.64 €/GJ (http://www.btgworld.com/en). This process has many upbeat features as mentioned by the company website. However, due to complete utilization of char for process heating, it may not be suitable for agricultural applications, where char (for CO_2 sequestration and soil enhancement) could have much higher added-value compared to bio-oil only orientation. Furthermore, high speed rotating cone (~600 rpm) may require considerable attention for operation and mechanical wear.

5.5. Ablative. Ablative pyrolysis reactors are being researched since 1980s; however, ablative pyrolysis is still under pilot scale studies due to its operational and scale up complexities [85, 92–96]. The ablative pyrolyzer requires simultaneous heating and surface renewal of the biomass feedstock via mechanical (rotating hot disc) or fluid dynamics (inert gas flow in wire mesh) (Figure 6). Mohan et al. [44] have correlated ablative pyrolysis to enhanced melting of a butter cube while pressing against a hot surface. It is said that the pyrolysis vapor and liquid produced during ablative pyrolysis can provide lubrication to the moving surface against which biomass is pressed; however, if the pyrolysis liquid stays longer on the rotating hot surface, it may undergo further undesired reactions. In order to avoid such reactions, fast removal of the pyrolysis vapor and liquids from the pyrolysis zone could nullify such lubrication effects. Ablative pyrolyzers could be based on direct contact [85, 94, 96, 97] or radiation ablation [92, 95]. The experimental reactors like wire-mesh reactor are more close to ablative reactor; nevertheless, the practical applicability seems to be
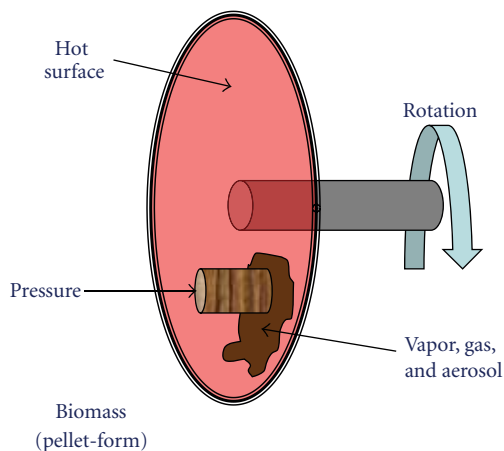
FIGURE 6: Ablative biomass pyrolysis reactor concept.

FIGURE 7: Vacuum pyrolysis reactor.

far from viable [92, 95]. On the other hand, direct contact ablative reactors appear to be practical but experiences with recent designs have been different from intuition. For example, in order to achieve flexibility in biomass types, extra biomass pretreatments are needed such as pelletization for fibrous biomass. High speed rotation of heated surface and sliding friction due to the intense pressure applied to the biomass pose great challenges to the scale up and operational simplicity.

5.6. Auger. Auger or screw pyrolyzer variants is getting increasing attention from many small and mid-size industries (Biogreen, [98] http://www.biogreen-energy.com/biogreen.html; EnerSysNet LLC, personal communication). The concept of solids handling using auger is integrated to almost all industries due to energy, space requirements, and related efficiencies. Interestingly, all other types of pyrolysis systems require auger unit to transport biomass at some point of process (feeding to the reaction chamber, char removal). However, application of auger concept to biomass pyrolysis is relatively recent. In fact, no pilot scale auger pyrolyzer was mentioned in the literature until early 2000s [12]. In this type of pyrolyzer, auger is used to transport the biomass through a heated (pyrolysis) zone (Figure 7). The biomass temperature is raised to the desired pyrolysis temperature during the transport through the heated zone by manipulating the auger rotation speed, diameter, flight-pitch, biomass particle size, and heating modes. The auger design provides a good control of biomass residence time inside the heated zone with minimal energy requirement. An apparent disadvantage could be moving parts and mechanical wear and tear; however, careful design (slow rotation) and developments in material science and machining (precision for tolerance and minimal contact between moving parts) can easily overcome this challenge. Auger pyrolyzers have major strengths in design compactness and simplicity, little or no carrier gas requirement, easy separation of bio-oil and char, and lower energy requirements. The simple operation of auger pyrolyzer is also an advantage from a farm scale utilization/application point of view. The recent surge in interest of small and mid-size industries
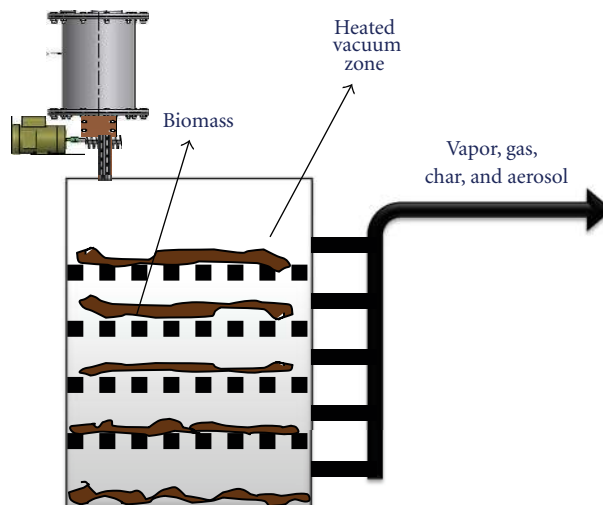
(including spinoffs from university research) is driven by the above-mentioned facts (BIOGREEN, EnerSysNet LLC, ROI LLC, Mississippi State University, Iowa State University). There are also several patents on auger reactor concept for the treatment of tire waste, municipal waste, and coal processing which justify the importance of auger design in the pyrolysis of biomass solids [99–107]. All of these pyrolysis systems work on the same principle, that is, pyrolysis reaction during transportation via auger/screw mechanism inside a heated zone, nevertheless, operating parameters (temperature, feedstock type, feedstock flow rates, particle size, use of sweeping gas, carrier material (sand/steel shots), direct or indirect heating among others), and pyrolysis system configurations vary greatly from one another. This also holds true for biomass pyrolysis systems.

5.7. Vacuum. The potential of vacuum pyrolysis for biomass as well as carbonaceous wastes has also shown some fruitful results after the pilot scale experiments [33, 108]. Vacuum pyrolysis does pose challenges such as lower heat- and mass-transfer, larger equipment size, and high capital investments which were required [109]. Also, maintaining fast pyrolysis conditions inside a vacuum pyrolyzer requires specials inlet and outlet design for feed material and pyrolysis products (Figure 8). Furthermore, continuous operation of vacuum pyrolyzer requires special feedstock input mechanism. These are huge discouragement to the potential investors and eventual commercialization. On the other hand, vacuum pyrolysis offers very good control over vapor residence time; therefore, it minimizes the secondary decomposition reactions of bio-oil. The rapid volatilization due to reduced pressure also enables in decreasing the pyrolysis temperature and a possible decrease in heat input. In the literature, vacuum pyrolysis has been depicted as able to utilize larger size biomass. It may be advisable to add up the advantage of vacuum or low intensity vacuum conditions inside other possible reactor configurations such as auger or ablative reactors
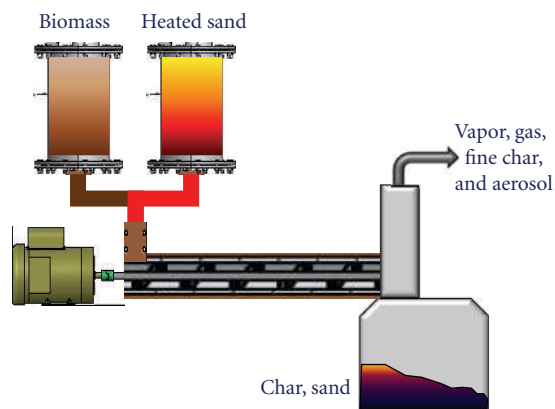
FIGURE 8: Auger/screw pyrolysis reactor concept using heat carrier.

to manipulate vapor residence time, pyrolysis temperature while also having better heat- and mass-transfer conditions.

6. Farm-Practice Concept for Residue/Waste Management via Pyrolysis

Farm residues/wastes can consist of up to 90% or more of organics/biomass [3]. This creates various opportunities to recover useful products via innovative management skills but also poses technical and economic challenges. Biological treatment of farm wastes is becoming increasingly challenging due to stricter regulations (limit to land spreading of biosolids due to metals and other nutrients) [9] as well as economic feasibility (increasing energy and utility cost). Anaerobic digestion provides energetic benefits to the agricultural producer; however, it is susceptible to various factors such as climate (low temperature), limited types and variations in waste composition, availability of land, among many. Most of the conventional farm waste disposal or transformation strategies falter either at technical or economic front. For example, composting of farm waste has many challenges such as control of odor, nutrient leaching, maturity, and net energy input [110, 111]. Pyrolysis of organic materials can have a potential of technical and can contribute to economic transformation of farm wastes into energy and valuable products, and sequestration of carbon. An overview of farm-scale application of pyrolysis for residue biomass management, transformation, and minerals and nutrient recycle is shown in Figure 9. Plants use CO_2 and sunlight to grow via photosynthesis as a natural process. The plant harvest could be diverted to food, valuable commodity, and animal feed. The animal farming requires animal feed (e.g., about 6 to 7 times plant biomass per unit mass of animal meat) and generates significant amounts of manure as farm wastes [112]. The animal manure could be separated via chemical or mechanical process into $\geq 60\%$ w/w solids and a liquid stream. The liquid stream could be further treated via biological process for removal of pathogens and toxic compounds and returned back to the soil, thereby, preserving water and soil minerals and nutrients (N and P). The biomass generated by the liquid treatment process and the

solids from the manure separation unit could be transferred to a drying unit. The drying unit should utilize energy from the combustion of the pyrolysis gases and should be able to reduce moisture to $\leq 10\%$ w/w. The pyrolysis unit could be operated by external energy source or could also utilize a portion of pyrolysis products (e.g., biochar and flue gases) to meet energy requirements. The bio-oil thus produced could either be used for heating and electricity generation for farm, or be sold to a bio-oil refinery network for purification and value addition. The biochar can be returned back to the soil to replenish minerals and nutrients as well as enhance physicochemical characteristics of soil such as pH, porosity, and density. Biochar has also been found to adsorb heavy metals and slow release of N, P, and other nutrients. This will help in enhancing the efficiency of fertilizers [56, 57, 113]. In addition, biochar has high self-life (100 to 1000 years), thus a significant portion of CO_2 from the atmosphere will be sequestered in soil with every crop cycle. This solution should be able to contain a significant part of the present GHGs emissions (agriculture sector contribute to about 8%) for a long term until a more comprehensive strategy is in place. In order to validate this scheme, life cycle analysis and technoeconomic study are currently being performed on the application of pyrolytic transformation of farm wastes (e.g., animal manure, plant residues) in our researches facility. In the past, there are only a few researches on pyrolytic conversion of farm wastes to bio-oil, biochar, and combustible gases [7]. However, the incumbent combined adverse effects of global warming/climate change, fossil fuel crisis, and risks to the environment have propelled the interests of governments and commercial sectors across the world towards the transformation of biomass residues and wastes into energy, carbon sequestration, and other valuable products. Many countries and conglomerates of countries have either initiated or at least planned subsidies and aid for biomass to energy concept. In most cases, the large scale commercial ventures are based on forest biomass/residue which may be suitable for long-term or sustainable development if they are well managed. At present, disposal and management of farm residue/wastes are major problems and should be actively considered as another important biomass source. As farm waste generation is related to the population consumption of farm goods which is growing rapidly, the transformation of farm wastes to energy, carbon sequestration, and valuable products could help in minimizing the net GHGs by decreasing the net use of fossil fuels.

7. Conclusions

The present study briefly reviewed various available technologies for thermochemical conversion of biomass to biofuels alternatives to fossil fuels and focused on biomass pyrolysis. Thermochemical processes have advantage over "biological only" processes where lingocellulosic biomass needs various pretreatment steps, time, and investments. At present, thermochemical processes such as gasification and combustion have a foothold at commercial scale for heat and electricity, mainly due apparent simple working principle and lack of research about their effect on sustainable
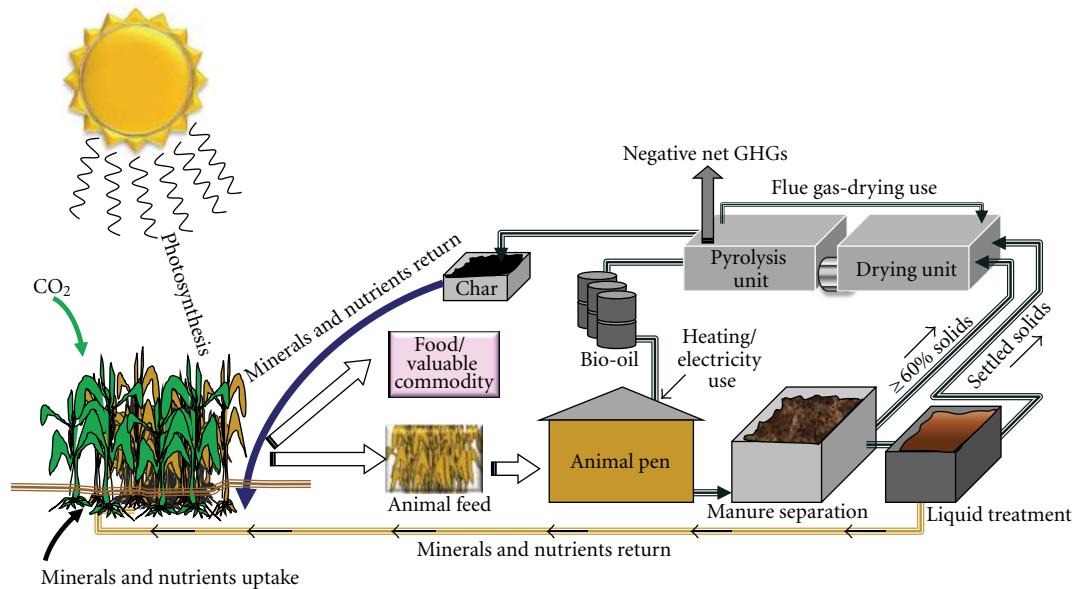
Figure 9: Possible farm practice of biomass residue.

development. However, in the recent years many studies have suggested biomass pyrolysis to be more favorable to the sustainable development in comparison to combustion and gasification. Biomass pyrolysis generates bio-oil, and biochar, which can have miscellaneous utilization such as energy, chemical feedstocks for industries, liquid fuels, carbon sequestration, bioremediation, and soil enhancement. On the other hand, gasification and combustion have limited uses to heating and energy. The established pyrolysis technologies at demonstration and commercial scale are fluidized bed variants and rotating cone types. Auger reactors for biomass pyrolysis are currently under laboratory, pilot, and demonstration stages and show good potential for mobile and farm scale uses due to simplicity of design and operation features. Ablative reactors need more research at laboratory scale and probably developments in material science to be successful at higher scale. The initial attempts with vacuum pyrolysis were successful despite challenges of lower heat and mass transfer, vacuum sealing requirements, and other operating and investment factors. Currently, vacuum pyrolysis can be considered to be a potential technology for commercialization. The physicochemical characteristics of bio-oil and biochar produced from pyrolysis are dependent on the biomass; however, the yields are related to pyrolysis reactor types and process used. A simplified farm-practice concept for waste management is depicted using biomass pyrolysis. This approach will produce bio-oil and biochar where bio-oil can be used for heating and electricity generation purposes and biochar can be applied for soil enhancement. Thus, a substantial portion of minerals and nutrients can be recycled back to the soil. Moreover, bio-oil will add to farm economy, and the overall process will be free of net energy requirement. However, these initiatives of biomass pyrolysis for sustainable development

will require subsidies and technology transfer for a successful venture.

Acknowledgments

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