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An Assessment of the Potential Use of Forest Residues for the Production of Bio-Oils in the Urban-Rural Interface of Louisiana

Yaw A. Twumasi[1*], Zhu H. Ning[1], John B. Namwamba[1], Edmund C. Merem[2], Abena B. Asare-Ansah[1], Harriet B. Yeboah[3], Matilda Anokye[1], Diana B. Frimpong[1], Priscilla M. Loh[1], Julia Atayi[1], Judith Oppong[1], Cynthia C. Ogbu[1], Rechael N. D. Armah[1], Caroline Y. Apraku[1], Opeyemi I. Oladigbolu[1], Joyce McClendon-Peralta[1]

[1]Department of Urban Forestry and Natural Resources, Southern University and A&M College, Baton Rouge, USA
[2]Department of Urban and Regional Planning, Jackson State University, Jackson, USA
[3]Department of Geography and Tourism Studies, Brock University, St. Catharines, Canada
Email: *yaw_twumasi@subr.edu, *yaw.twumasi@gmail.com

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Abstract

Louisiana is endowed with forest resources. Forest wastes generated after thinning, land clearing, and logging operations, such as wood debris, tree trimmings, barks, sawdust, wood chips, and black liquor, among others, can serve as potential fuels for energy production in Louisiana. This paper aims to evaluate the potential annual volumes of forest wastes established on detailed and existing data on the forest structure in the rural-urban interface of Louisiana. It also demonstrates the state's prospects of utilizing forest wastes to produce bio-oils. The data specific to the study was deduced from secondary data sources to obtain the annual average total residue production in Louisiana and estimate the number of logging residues available for procurement for bioenergy production. The total biomass production per year was modeled versus years by polynomial regression curve fitting using Microsoft Excel. Results of the model show that the cumulative annual total biomass production for 2025 and 2030 in Louisiana is projected to be 80000000 Bone Dry Ton (BDT) and 16000000 (BDT) respectively. The findings of the study depict that Louisiana has a massive biomass supply from forest wastes for bioenergy production. Thus, the potential for Louisiana to become an influential player in the production of bio-based products from forest residues is evident. The author recommends that future research can use Geographic Information Systems (GIS) to create maps displaying the potential locations and utilization centers of forest wastes for bioenergy production in the state.

Keywords

Bioenergy Production, Bio-Oils, Polynomial Regression, Bio-Products, Forest Residues, Logging Residues, Wood Wastes, Louisiana

1. Introduction

Louisiana has long been acknowledged for the production of oil and gas. The state has fully developed into a globally accepted hub for the restoration, processing, and transportation of fossil fuels, specialty products, and chemicals after producing oil wells in Jennings in 1901 and the natural gas pipeline adjacent to Shreveport in 1908. Over time, more than a million producing wells have been drilled by the state, which has made billions and trillions of barrels of oil and cubic feet of natural gas, respectively. Being a producer of almost 23% of the nation's crude oil and 11% of its gas, the sector has persistently become a major economic driver in Louisiana and beyond the Gulf of Mexico region. Nonetheless, the global reliance on non-renewable fossil fuels combined with issues about climate change has drawn attention to an alternative which is the renewable and biobased sources of energy (Benedict & Russin, 2015).

The urban-rural interface of Louisiana is envisaged as a peri-urban passage zone with different sources of income, spatial uses, movement of people, information, natural resources, financial assets, and waste products between urban and rural areas. This zone correlates with the site of direct influence of the city where the impacts of urban sprawl and pollution are directly experienced (Ros-Tonen et al., 2015). Forest resources encompass an important aspect of the culture of Louisiana. The state covered 9% of all forest areas in the eight (8) states of the South-Central United States in 2012. Historically, before European settlement in the 17th century, Louisiana was almost 100% forested. However, the clearing of agricultural products from the 1800s through the 1970s for development led to continuous reductions in the total land surface of the forests throughout the 1990s. Presently, forests cover approximately 55% of the topography of Louisiana, which is virtually used for timber production. Whereas the northwest, southwest, and southeast units are heavily forested, the south and north Deltas, which represent the center of the state's agricultural production, remain the least (Oswalt, 2013).

The United Kingdom (UK) Environmental Agency (2012) defines waste as any substance disposed of intended to be gotten rid of or required to be thrown away. Nevertheless, concerning sustainable development, waste is considered a resource useful for producing countless resource products. Forest wastes are residues from forest harvesting, a major raw material of biomass for energy production. It includes forest activities such as thinning, cutting, clearing lands, and others, which generate yield tops and branches for bioenergy production (Belyakov, 2019). Kizhakkepurakkal (2013) highlights that Louisiana has approximately one hundred and eighty (180) primary forest product facilities, consisting of veneer, plywood, panel, paper, and sawmills. Biomass wastes in the form of bark, sawdust, and wood chips are natural sources of raw materials. The use of wood and forest wastes as raw materials for bio-products, according to Digital Data Systems (Pty) Ltd. (2016), will reduce the consumption of fossil fuels, leading to a decline in the discharge of greenhouse gases to the environment. Wood residues and forest wastes are ideal sources of bioproducts because they are non-pollutant, pure, and neutral in carbon dioxide excretions. The American Council on Renewable Energy (2011) explains that Louisiana has taken on several clean energy bills and tax incentives to increase its share in biomass energy production. One of the policies is about $124 million worth of wood pellet plants to produce 450000 metric tons of wood pellets annually to be transported as bioenergy to Europe. Additionally, over three hundred (300) jobs and $12. 9 million in state taxes are projected to be generated from this activity over the next ten years (ibid).

According to Cardoso et al. (2011), it is estimated that 14% of the total energy demanded globally is covered by biomass. Energy has always been an essential resource in the existence of humanity. Ever since human history, it has had various forms, such as wood, coal, hydropower, nuclear energy, fossil fuels, etc. However, in the last couple of decades, crises of environmental degradation due to the overutilization of these resources have brought about major catastrophes like climate change and environmental pollution, among others. Therefore, it is imperative to develop a sustainable and environmentally friendly solution (Kizhakkepurakkal, 2008). In the United States, forests are expanding. Forest biomass presently grows at about three percent annually, creating a great opportunity for the forest products industry. Hence, residue from these industries can be a possible energy source to operate the industry. Due to the expansion of forests in the United States, wastes from the forest products industry define a renewable and sustainable energy resource. Thrä & Kaltschmitt (2002) also assert that forest wastes such as bark and sawdust are the most extensive commercially utilized biomass source for biofuel production.

Depending on their origin, forest wastes for bioenergy production can be largely categorized into logging residue and residue from the forest products industry. Logging residue is produced at timber harvest sites after trees have been felled. Although logging residues can be considered in bioenergy production, it is costly. Moreover, the residues may pollute the environment (Hakkila, 1989, cited in Kizhakkepurakkal, 2008). Wood residue from the forest products industry, on the other hand, incorporates all wood residue yielded from the industry. It can also be divided into primary and secondary industries residues used for energy production based on the origin. In the sawmill and plywood industry, the wood residue is estimated to represent 45% - 55% of the timber input (FAO, 2012, cited in Kizhakkepurakkal, 2008). Louisiana's primary forest products industry includes sawmills, plywood mills, panel mills, veneer mills, and pulp/paper mills dispersed throughout the state. A by-product of this industry comprises forest wastes such as bark, wood chips, and sawdust. Jointly they produce more than seven million tons of wood residues annually. For bioenergy production, the industry mostly utilizes lumber-drying kilns or veneer driers (Kleit et al., 1994, cited in Kizhakkepurakkal, 2008). Secondary industries (cabinet shops, architectural millwork, furniture manufacturers, etc.) produce 80000 tons of wood residues yearly (equivalent to energy use in 17000 homes). These comprise dry wood trimmings, sawdust, and sander dust, making them feasible for energy production. However, almost all these materials go unused. The purpose of this paper is to assess the potential annual volumes of forest wastes based on detailed and existing data on the forest structure in Louisiana's rural-urban interface. It also shows the state's potential for using forest waste to produce bio-oils. Having more than 530 forest product industries, Louisiana has the potential to transform forest wastes into bioenergy (Kizhakkepurakkal, 2008).

2. Problem Statement

Yue and Smyder (2014) explains that a rise in the use of forest wastes for bioenergy production may increase demand for alternative feedstock, such as logging residue, which will require technological equipment advancements to haul and utilize it to produce fuel. However, the need for more specialized equipment may increase the cost of obtaining logging residues and dissuade mills from using this feedstock. It has been challenging and expensive to collect and use logging residues because of high transportation costs and the lack of appropriate equipment to gather, pack, store, and process them (Pokharel et al., 2017). Nearly 35% of the cost of utilizing logging residues for bioenergy can be allocated to its acquisition (Perez-Verdin et al., 2009). The decline in transportation costs and haul time can increase the supply and usage of forest waste products such as logging residues (Alam et al., 2012). Even though hauling dry logging residues can lessen transport costs, logging residues in the southern United States are conveyed to the mills without drying; hence, logging operators are remunerated per green weight. Similarly, Waste to Wisdom (2018) suggests that the moisture content of forest wastes is one of the elements that obstruct the growth of bio-oil production. These residues contain water, determining the raw material's overall heating value. Besides, drying demands advanced heating machinery and storage space close to the site (ibid). Consequently, the lack of storage space and equipment to dry logging residues could make their collection and processing challenging.

Additionally, the shortage of efficient and suitable equipment to manage logging residues and mills could restrict their utilization (Pokharel et al., 2019). According to Hoefnagels et al. (2017), the improper disposal, utilization, and management practices associated with the handling of forest wastes are neither efficient nor universally applied, thus, making it a burgeoning challenge. Especially in developing countries, most forest wastes are left in the fields to decompose or openly burn, polluting the environment. Comparably, with the rise in urbanization and demand for construction products, alternative raw materials for sustainable energy are required. To date, the underutilization of forest wastes for energy production has limited activities which focus on a low carbon route for their optimization.

A knowledge gap exists within the landscape of bio-oil production from forest wastes in the rural-urban interface of Louisiana—many works of literature focus solely on either the rural or urban scope. There has also been a rise in the published literature on the utilization of wood residues to produce bio-oils and bio-products in the state. However, scholarly documentation on the use of forest wastes as raw materials for production is limited, which will be a gap in the research. This article seeks to provide a bridge to the current knowledge gap that exists in the subject area. Consequently, this paper aims to assess the potential annual volumes of forest wastes based on comprehensive and current data on the forest structure in the rural-urban interface in Louisiana and demonstrate the potential of forest wastes to produce bio-oils in the state.

3. Forest Wastes in Louisiana

Forest wastes are feasible substitutes for converting energy into fuels, heat, or electricity because they are less expensive, they do not compete for food, and significantly, they have an energy balance close to zero (Carrasco-Diaz et al., 2019). Similarly, Sedjo (1997) suggests that to curb the costs and environmental issues associated with fossil fuel, processed forests and woody biomass have become good sources of bio-based wood products and energy. Biomass from forest waste can be grouped into three supply chain components: primary, secondary, and tertiary. The primary forest biomass sources are fuels from forestland, thinning, land clearing, and logging residues. The secondary and tertiary sources of forest biomass include processing mill residues (primary and secondary mills) and the construction and demolition of wood debris, tree trimmings, packaging, and consumer waste, respectively (FAO, 2012).

Louisiana is resourced with over 13.8 million acres of forestland. It has been speculated that the waste products generated after logging could provide over 3 million dry tons of biomass annually. In this state, bark, sawdust, and other debris, which constitute 98% of the milling residues, are used for energy production. In contrast, the remaining 2% provides tons of wet biomass every year (Jackson, 2003). The combination of Louisiana's forestry and agricultural industries contributes about 7% of the gross state product. Throughout each year, the processing of a variety of crops generates billions of dollars, provides consumer products, and creates a prominent job market. According to Greene and Brasher (2020), Louisiana has 14 million acres of forest cover, which is half of the state's total land surface area, making it the greatest single land use. About fifty-nine (59) out of the state's sixty-four (64) parishes provide adequate raw materials from the land to support its forest products industry, making it the second-largest manufacturing employer, which provided more than 12000 jobs in 2012. Moreover, eight thousand (8000) people were employed to harvest and transport timber [ibid].

Kizhakkepurakkal (2012) argues that most wood biomass fuel used for energy production in forest industrial and other logging operations is essentially from forest wastes. On some occasions, waste from wood is generated from thinning operations to improve forest health and the value for which they are harvested after forest operations. Unfortunately, harvesting these residues may cause nutrient exhaustion, affecting the fertility of the land. Economically, such activities may not be feasible. Supposedly, only three-quarters of the logs are transformed into processed products concerning the waste products collected from the forest. The remaining part consists of residues like bark, sawdust, wood chips, and black liquor, which can serve as potential fuels for energy production.

4. The Potential Utilization of Forest Wastes for Bio-Oil Production

Since the late twentieth-century oil crisis, significant attempts have been made to transform wood biomass into liquid fuels and chemicals (Mohan et al., 2006). According to Xu et al. (2011), bio-oil research has garnered much interest in recent years because of its sustainable, carbon-neutral, and simple-to-store transport properties. Consequently, several technologies for preparing and upgrading bio-oil have been developed, including rapid pyrolysis, liquefaction, gasification, and hydro treatment. Furthermore, bio-oil characterization is being worked on and has made considerable progress. Thermal processing may transform biomass into various products. One of them is bio-oil, a highly oxygenated liquid that is readily transported and storable and can be processed into higher added value compounds such as phenols, ketones, aldehydes, and alcohols, in addition to energy and fuel. The material is made by submitting biomass to pyrolysis, a method characterized by thermal degradation (temperatures over 400˚C) in the absence of an oxidizing agent (total or partial) such that no gassing occurs (Bridgwater, 2012).

Fast pyrolysis, liquefaction, and gasification processes may be used to convert biomass to bio-oil and upgrade, and separation procedures can generate high-quality products. These procedures result in varied product qualities, owing to technological and equipment variances (Dalla et al., 2016). Pyrolysis as a method of producing bio-oils has been researched extensively for the past 30 years. One of the major benefits of this process is that it may utilize a wide range of raw materials, including industrial wastes. Forest leftovers are one example (Environmental Engineering Research, 2021), Yang et al. (2013) assert that if generated and treated appropriately, pyrolysis oil or bio-oil produced from biomass pyrolysis has been recognized as a possible fuel to replace fossil fuel in numerous applications. Wood, agricultural waste, forest leftovers, and municipal solid waste may all produce bio-oil. The amount of cellulose, hemicellulose, and lignin in the biomass impacts bio-oil production and chemical composition. This biomass composition has various thermal properties that are influenced by the pyrolysis process's heating rate (Czernik & Bridgwater, 2004).

In line with most countries' biomass energy programs to produce energy and mitigate greenhouse gas emissions through forest-based activities are four (4) strategies—increasing the density of carbon in existing forest areas, reducing emissions from deforestation, practicing reforestation, and using forest products that credibly replace fossil fuels (Canadell & Raupach, 2008). Brosowski et al. (2016) explain that residues from bio-products and waste pile up in many areas of business and society. The range stretches from agriculture and forestry to manufacturing and urban waste. Bio-products reveal some fascinating alternatives to promote the efficiency of already established waste products, such as the production of basic chemicals and sustainable energy.

Hoefnagels et al. (2017) writes that the growing demand for food and other necessities from an increasing population has intensified agricultural and industrial activities. The improper disposal, utilization, and management practices associated with the handling of forest wastes are neither efficient nor universally applied, thus, making it a burgeoning challenge. Especially in developing countries, most forest wastes are left in the fields to decompose or openly burn, thereby polluting the environment. Comparably, with the rise in urbanization and demand for construction products, alternative raw materials for sustainable energy are required. To date, the underutilization of forest wastes for energy production has limited activities which focus on a low carbon route for their optimization. Waste products from the forest are used for several purposes. However, they are site-specific. Aside from being used for fuel production, they are also used as fertilizer, soil conditioners, fodder, fiber, and feedstock. Supposedly, residues are free to waste products and are of no use. However, practically, these waste products freely available in monetized economies can acquire a monetary value when used efficiently (Koopmans & Koppeian, 1997). According to Waste to Wisdom (2018), forest wastes such as minute trees, limbs, and tops from thinning and timber harvest operations can be used as raw materials to produce renewable bioenergy and bio-products.

Additionally, the efficient utilization of forest wastes could cancel out the high costs associated with restoring the treatment of fire hazards and the management of the forest in general. Due to their high assemblage and transportation costs and low market value, forest resources have been treated as waste materials for which they have not been fully utilized. Consequently, open burning to dispose of forest wastes has had a negative impact on the environment in terms of increased forest management costs and air pollution. Similarly, Vogt et al. (2005) suggest that the production of renewable energy from locally harvested biomass could reduce energy shortages and give rural community members living in or near forests the opportunity to engage in other economic activities. The use of forest wastes over agricultural wastes to produce bio-products is quintessential because of its ability to create higher efficiencies of biofuel conversions. Compared to other tree species in terms of variation in chemical composition, forest wastes are ideal for producing biofuels. Forestry-based bioenergy programs are now regarded as feasible alternative approaches to producing energy because they are environmentally sustainable, economically prudent, and socio-politically acceptable.

5. Data and Methodology

The data for the average total logging residue production (BDT) in the sixty-three (63) parishes in Louisiana from the years 2000 to 2010 were obtained from Kizhakkepurakkal's (2012) study. In the subsequent years, secondary data was drawn from research by Wall et al. (2017) and the USDA Forest Service (2020a; 2020b; 2021a; 2021b). Also, data used in this update on the statistical analysis estimates of logging residues available for procurement in Louisiana was accessed from a study by Pokharel et al. (2019). Finally, data on Louisiana's oil production and operable refinery capacity was acquired from Sutherlin's (2009) analysis, which describes Louisiana's alternative energy policy to discuss the state's potential in utilizing forest residues for bio-oil production.

6. Modeling of Total Annual Logging Residue for Louisiana

The total biomass production per year for all counties of Louisiana and their corresponding years were extracted from **Table 1**. The total biomass production per year was modeled versus years by polynomial curve fitting using Microsoft Excel.

7. Results and Discussion

7.1. Average Total Logging Residue Production (BDT) in Louisiana (2000-2010)

With reference o **Table 1**, the average total production for logging residue from 2000 to 2010 was approximately 3073978. Overall, six Parishes, Winn (158404 bdt), Vernon (154955 bdt), Bienville (142258 bdt), Union (141772 bdt), Beauregard (133322 bdt) and Sabine (130248 bdt) topped the logging residue production in the state (Kizhakkepurakkal, 2012). These parishes located in the Western and Northern parts of the state in combination produced around 28% of the total logging residue. On the contrary, Vermilion, St. Mary, St. John the Baptist, St. Bernard, and Plaquemines recorded the least amount of logging residues. Logging residue was produced the most in 2006 (3459393 bdt), followed by 2003 (3456919 bdt) then 2000 (3335445 bdt). In descending order, the bottom three years that recorded the least production of logging residue are 2008 (2800845), 2009 (2634553), and 2010 (2634553). The production of logging residue fluctuated from 2000 to 2010, increasing and decreasing over the years.

Table 1. Average total logging residue production (BDT) in Louisiana (2000-2010) (Kizhakkepurakkal, 2012).

Parish	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Average
Acadia	23594	11544	29948	12472	7456	4781	10223	11544	5150	5278	2656	11331
Allen	152846	101588	116222	142282	129604	116993	108074	101588	93475	77294	102936	112991
Ascension	14096	6130	4799	14197	17986	6582	21622	6130	5192	7788	5060	9962
Assumption	152	1186	4298	1452	1080	421	1920	1186	1525	1909	4604	1794
Avoyelles	11054	52358	32613	53351	34689	58448	29378	52358	30580	52114	32533	39952
Beauregard	142632	129517	140088	143643	117561	125691	168391	129517	130373	106521	132613	133322
Bienville	126782	138653	133641	168400	164883	170344	163556	138653	124270	112370	123287	142258
Bossier	126962	63098	68065	88069	75459	99222	77236	63098	52017	49269	68469	75542
Caddo	78048	50990	69691	63544	53490	62620	48114	50990	57177	45669	40921	56478
Calcasieu	50500	16807	23567	32953	34131	46804	59820	16807	29182	15290	19463	31393
Caldwell	84216	103038	67755	62448	53533	66658	67479	103038	63487	89367	69376	75490
Cameron	65	477	3703	11429	12020	23080	269	477	89	187	0	4709
Catahoula	32853	60556	23233	34686	40756	35753	23781	60556	21159	42206	12254	35254
Claiborne	94801	100077	130079	145685	113204	132824	102283	100077	103313	87759	106820	110629
Concordia	25118	27910	38594	56987	46655	39767	31632	27910	18581	17729	12973	31260
De Soto	136867	111972	98384	100641	100080	112831	108261	111972	95857	98579	104594	107276
East Baton Rouge	22119	37808	27195	32031	29390	36872	28845	37808	23450	28314	14322	28923
East Carroll	19823	20679	16601	31828	14570	10526	10527	20679	4469	15025	1746	15134
East Feliciana	53960	58017	40811	82947	55244	49533	38282	58017	66165	50943	47346	54660
Evangeline	78444	36940	48093	43129	55819	42899	50591	36940	60509	44099	52196	49969
Franklin	22895	17754	8482	13135	8283	18716	14192	17754	5853	10724	12968	13705
Grant	40715	42784	29104	43808	56175	48352	59308	42784	63507	38359	49204	46736
Iberia	1637	6769	241	1139	1419	1393	526	6769	101	6032	0	2366
Iberville	117117	34094	23713	50909	37824	58394	40120	34094	12327	39249	19551	42490
Jackson	112872	91252	98849	156750	151765	141052	160110	91252	118803	85036	74303	116549
Jefferson	919	2019	714	7197	10418	12732	12882	2019	396	850	101	4568
Jefferson Davis	14948	4387	5309	9481	6354	7566	5263	4387	6464	2625	7469	6750
Lafayette	5199	650	386	2679	1084	2248	1424	650	356	577	252	1410
Lafourche	1315	1422	1936	255	723	2928	3585	1422	9151	1555	8076	2943
La Salle	107392	91404	80038	68195	79901	81380	81717	91404	66282	81476	83038	82930
Lincoln	61104	60537	69677	63481	92953	76519	80216	60537	67134	53078	58902	67649
Livingston	116199	92515	68019	110450	58697	48059	83636	92515	65526	94278	51514	80128

Continued

Madison	54493	53014	44805	28455	9598	13660	31397	53014	43595	39001	29480	36410
Morehouse	41476	42298	49216	54944	45657	48533	53225	42298	53264	33412	26840	44651
Natchitoches	110019	86584	111459	102281	103190	113289	128941	86584	116562	74161	91211	102207
Orleans	0	1481	497	301	1968	3612	2332	1481	550	1455	1090	1342
Ouachita	63418	41844	48121	50571	46270	68263	63730	41844	28023	39729	45095	48810
Plaquemines	180	186	1274	141	250	166	126	186	326	14	18	261
Pointe Coupee	27308	50266	60372	69173	47234	63596	37847	50266	29642	52553	29205	47042
Rapides	104733	99567	72719	89952	84277	79072	85539	99567	78501	80946	104259	89012
Red River	18346	16326	37772	34857	28860	40317	44935	16326	37818	15979	32169	29428
Richland	24400	14042	17129	22590	12728	15792	10117	14042	7290	10694	9289	14374
Sabine	108828	116424	135709	142632	152489	147151	152658	116424	126294	107812	126302	130248
St. Bernard	14	371	2150	30	417	81	124	371	0	230	0	344
St. Charles	2276	253	997	7237	8357	7352	2617	253	297	151	27	2711
St. Helena	59783	67370	64400	49293	57214	29894	41802	67370	55660	68829	63185	56800
St. James	4012	7901	10815	4708	5513	6454	8703	7901	4719	7537	3631	6536
St. John the Baptist	18	278	32	965	2242	802	142	278	32	269	5889	995
St. Landry	26675	54042	54309	42804	30938	41829	39016	54042	59527	58978	84462	49693
St. Martin	2710	6923	1253	7648	6573	13545	29182	6923	17814	9070	13457	10464
St. Mary	1576	12	106	41	1911	9	671	12	143	61	256	436
St. Tammany	37139	20534	17227	39949	35709	40441	79492	20534	33653	15772	11388	31985
Tangipahoa	63947	56488	54057	61771	51668	51061	86278	56488	41148	43184	36828	54811
Tensas	26653	56732	15431	37743	23026	36566	39177	56732	18876	47657	38142	36067
Terrebonne	62	370	263	1295	1312	6226	1475	370	3439	444	1560	1529
Union	151554	165572	141943	144229	128253	146553	149236	165572	117233	136803	112550	141772
Vermilion	2391	1246	159	1873	1371	9102	1200	1246	743	218	9801	266
Washington	76958	70127	89837	86562	72542	54454	146545	70127	30358	66263	37770	72868
West Baton Rouge	12280	10916	9698	8599	8123	31807	29338	10916	22695	9755	7636	14706
West Carrol	9836	9593	16250	12093	11110	11202	6663	9593	4504	8450	2417	9246
West Feliciana	53663	46055	39459	45321	46303	41377	35803	46055	49231	40875	24258	42582
Winn	114850	143793	129052	167544	187782	175712	222615	143793	195476	130685	131146	158404
Total	**3335445**	**3060489**	**2988921**	**3456919**	**3088433**	**3262881**	**3459393**	**3060489**	**2800849**	**2665385**	**2634553**	**3073978**

7.2. The Output of Industrial Products and Species Groups in Louisiana (2013 and 2015)

Table 2 shows the results of a 2015 canvass of all primary wood-using plants in Louisiana and describes the transformations in product output and residue use since 2013. It completes the Forest Inventory and Analysis (FIA) annual inventory of volume and disposals from the state's timberland. The canvass was carried out to specify the quantity and origin of wood receipts and yearly timber yield drain in 2015. Primary wood-using mills were exclusively canvassed. Primary mills process roundwood in log or bolt form or as chipped roundwood. The industrial roundwood products included saw logs, pulpwood, veneer logs, poles, and logs used for combined board products. Trees chipped in the woods were included in the calculation of timber drain only if they were supplied to direct domestic manufacturers (Wall et al., 2017). Overall, there was a 2% reduction in the total industrial products from primary wood-using plants in Louisiana in 2013 and 2015.

7.3. Primary Products in Louisiana Mills

As shown in Tables 3-5, in 2015, the processing of primary products in Louisiana mills yielded 172.4 million cubic feet of wood and bark remains. Coarse residues comprised 75.9 million cubic feet from all direct products, while bark volume summed up to 36.4 million cubic feet. Synthetically, sawdust and shavings constituted 60.2 million cubic feet, which makes up 35% of the total remains. The processing of saw logs yielded 98.1 million cubic feet of mill residues, representing 59% of the total residues produced. Almost all the wood and bark

Table 2. The output of industrial products and species groups in Louisiana (2013 and 2015) *MCF (Thousand cubic feet).

Product and species group	2013 (MCF)	2015 (MCF)	Difference	Percentage change
Saw logs	137884	143120	5236	3.8
Veneer logs	117105	99771	−17334	−14.8
Pulpwood	356531	318340	−38.191	−10.7
Bioenergy	10879	40015	29136	26.8
Other industrial	45141	53218	29136	17.9
All industrial	667541	654465	−13076	−2.0

Table 3. Primary mill residue types, Louisiana, 2015 (Wall et al., 2017).

Residue type	Percentage (%)
Coarse	44
Saw dust	28
Bark	21
Shavings	7

residues were used to manufacture a product. Eighty-six percent, or 64.9 million cubic feet, of the coarse residues were manufactured into fiber products (Wall et al., 2017).

7.4. The Statewide Roundwood Production by Product in Louisiana

Figure 1 and Table 6 display the statewide roundwood production of pulpwood, sawlogs, veneer logs, miscellaneous, bioenergy, and poles in 2017, 2018, 2019 and 2020. Pulpwood has always been the most produced roundwood from 2017 to 2020, followed by saw logs and veneer logs. On the other hand, poles were produced the least in all the years. The production of poles has always been less

Table 4. Primary mill residue produced by roundwood type, Louisiana, 2015 (Wall et al., 2017).

Residue type	Percentage (%)
Saw logs	59%
Veneer logs	36%
Other industrial	3%
Pulpwood	2%

Table 5. Disposal of residue by product, Louisiana, 2015 (Wall et al., 2017).

Product type	Percentage (%)
Industrial fuel	58%
Fiber/composite products	40%
Mulch/soil additive	2%
Sawn products	<1
Animal bedding	<1
Not used	<1

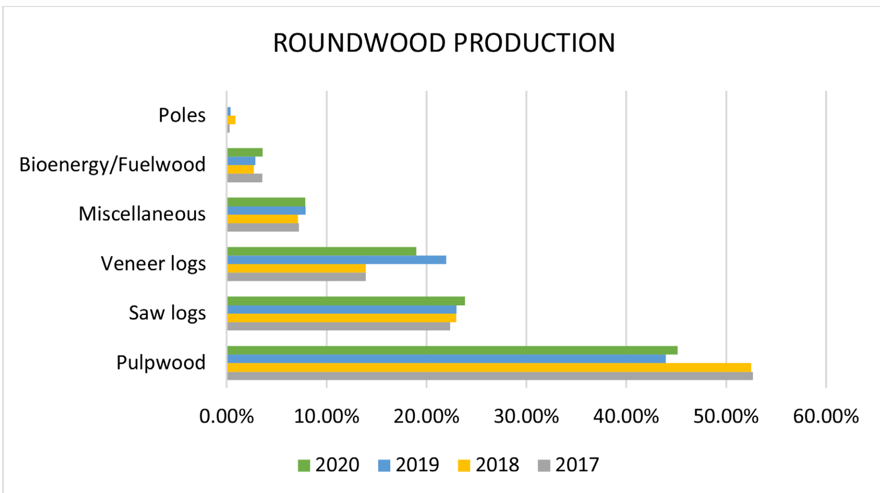

Figure 1. Statewide roundwood production (% of total) by product.

than 1% in the state.

7.5. Available Logging Residues for Procurement

Table 7 presents the procurement zones for 5-, 10-, 15-, 20-, 25-, 30-, 35-, 40-, 45-, 50- 55-, and 60-mile hauling distances and estimates of logging residues' physical availability at these hauling distances as well as the percentages of total physically available logging residues in Louisiana. On average, mills in Louisiana would potentially be able to cover 75% [128 bone dry tons (bdt)] of available logging residues within a 5-mile, 25% (473 bdt) within a 10-mile, 48% (916 bdt) within a 15-mile, 71% (1347 bdt) within a 20-mile, 85% (1612 bdt) within a 25-mile, 91% (1725 bdt) within a 30-mile, 95% (1794 bdt) within a 35-mile, 97% (1835 bdt) within a 40-mile, 98% (1857 bdt) within a 45-mile, 99% (1877 bdt)

Table 6. Statewide roundwood production (% of total) by-product (USDA Forest Service, 2020a; 2020b; 2021a; 2021b).

ROUNDWOOD PRODUCTION	2017	2018	2019	2020
Pulpwood	52.67%	52.47%	43.95%	45.10%
Saw logs	22.37%	22.94%	22.97%	23.84%
Veneer logs	13.90%	13.90%	21.97%	18.98%
Miscellaneous	7.22%	7.11%	7.89%	7.85%
Bioenergy/Fuelwood	3.55%	2.69%	2.85%	3.60%
Poles	0.29%	0.88%	0.37%	0.63%

Table 7. Results Quantities of Logging Residues Physically Available for Procurement, (Pokharel et al., 2019).

Hauling distance (miles)	Quantity of recoverable logging residues (1000 bone dry tons per year) from a milling facility	Percentage of total physically available logging residues (%)
5	128	7
10	473	25
15	916	48
20	1347	71
25	1612	85
30	1725	91
35	1794	95
40	1835	97
45	1857	98
50	1877	99
55	1888	100
60	1892	100

within a 50-mile, 100% (1888 bdt) within a 55-mile and 100% (1892 bdt) within a 60-mile procurement zone yearly. Figure 2 illustrates the model for the quantities of logging residues physically available for procurement versus the hauling distance.

As the model in Figure 2 suggests, the availability of logging residues varies positively with the hauling distance according to a quadratic model. However, it should be noted that after 50 miles, it is approximately equal to 100%.

7.6. Annual Biomass Production in Louisiana

Table 8 presents the total biomass production for all parishes in Louisiana and their corresponding years. The total biomass production per year was modeled versus years by polynomial curve fitting using Microsoft Excel. The model is

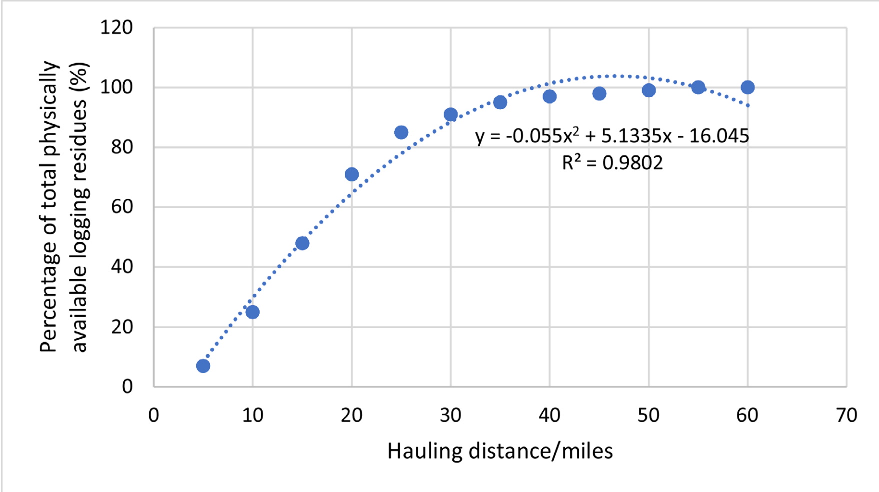

Figure 2. Percentage of total physically available logging residues (%) versus hauling distances.

Table 8. Total biomass production per year was modeled versus years.

Year	Total
2000	3335445
2001	3060489
2002	2988921
2003	3456919
2004	3088433
2005	3262881
2006	3459393
2007	3060489
2008	2800849
2009	2665385
2010	2634553

presented in Figure 3.

This model (Figure 3) represents only 61% of the data.

A better model was produced by computing annual total productions based on the total annual average for each 2 consecutive years. The data resulting from this computation and the model are presented in Table 9 and Figure 4. The model displayed in Figure 4 suggests that the total annual biomass was approximately constant from 2000 to 2006. It then started to decrease.

However, these two models (Table 9 and Figure 4) suggest the total annual biomass production is projected to decrease to zero soon. Extrapolation of these models using Microsoft excel predicts the total annual biomass production to decrease to 0 before 2040. Biomass can only reduce to zero if either none is produced or if all of it is utilized in other applications other than being available for bioenergy production. Let it be assumed here that the state of Louisiana will

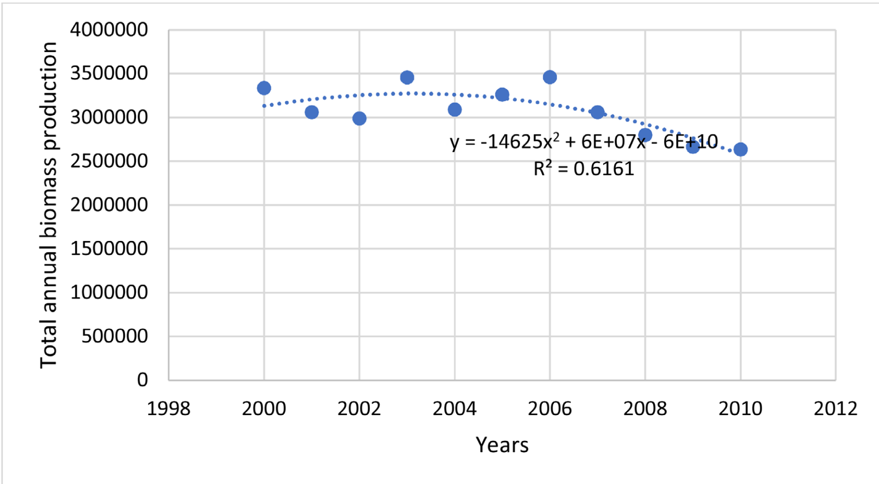

Figure 3. Total annual biomass production versus years (quadratic model)

Table 9. Total annual total productions based on the total annual average for each 2 consecution years.

Year	Average
2001	3197967
2002	3024705
2003	3222920
2004	3272676
2005	3175657
2006	3361137
2007	3259941
2008	2930669
2009	2733117
2010	2649969

always have biomass residue, regardless of the quantity. To avoid the modeled biomass quantity from decreasing to zero, a prediction method introduced was used (Namwamba et al., 2022). Computation of annual cumulative biomass was carried out and presented in **Table 10** and **Figure 5**. Modeling of cumulative annual biomass produced was then carried out by polynomial curve fitting using Microsoft Excel.

The total annual cumulative biomass from Louisiana (**Table 10**) was modeled versus years, using Microsoft statistical tool. The model is illustrated in **Figure 5**.

The model in **Figure 6** explains approximately 100% of the data. The model also suggests the availability of biomass every year.

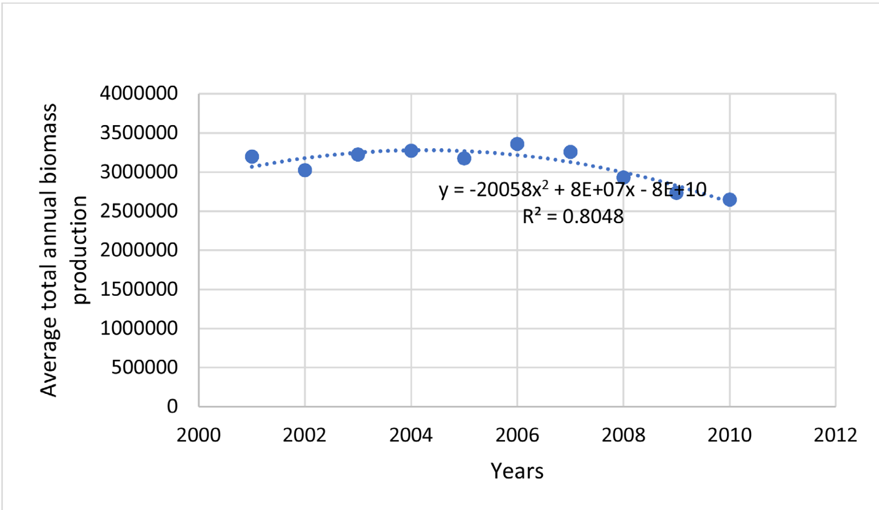

Figure 4. Model for total annual total productions based on the total annual average for each 2 consecutive years versus years (Louisiana).

Table 10. Total annual cumulative biomass produced in Louisiana for period 2000-2010.

Year	Louisiana cumulative biomass
2000	3335445
2001	6395934
2002	9384855
2003	12841774
2004	15930207
2005	19193088
2006	22652481
2007	25712970
2008	28513819
2009	31179204
2010	33813757

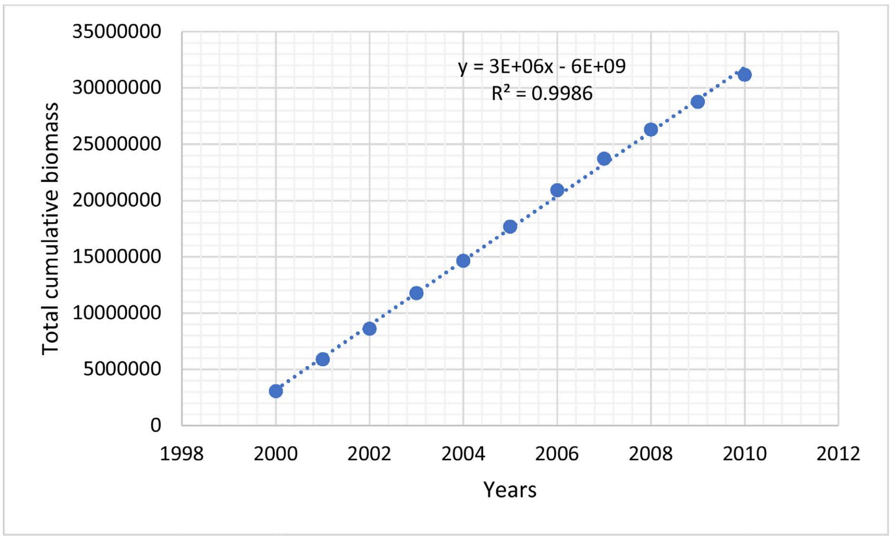

Figure 5. Total cumulative annual biomass produced in Louisiana versus years linear model (2010-2030).

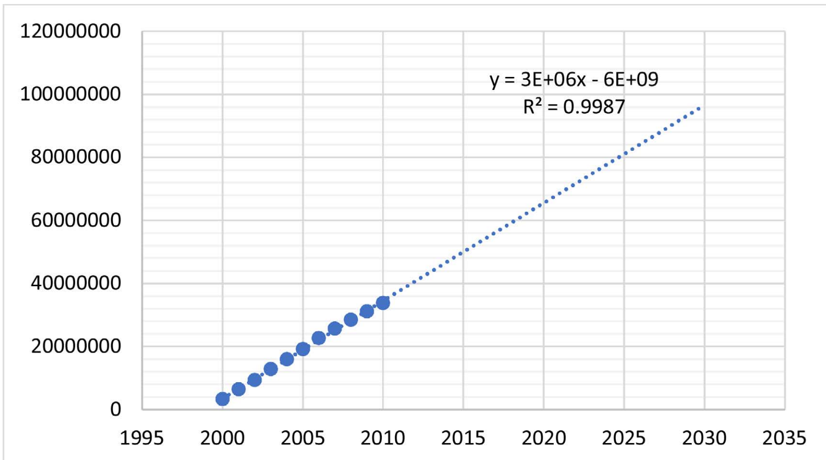

Figure 6. Total annual cumulative biomass versus years (extrapolated model 2020-2030).

The fitted line was extrapolated for use in predicting annual biomass production in Louisiana beyond 2010. The cumulative total annual biomass can be predicted directly using the model illustrated in Figure 6. To illustrate the use of the predictive model, consider the year 2025. The predicted cumulative total annual biomass is the vertical coordinate of the point of intersection between the regression line and the perpendicular line through 2025 (Figure 6). Hence, the cumulative total annual biomass in 2025 is 80000000 (BDT).

The expected total annual biomass yield for all Louisiana's counties for the n year is determined from the following function.

$$M = f(x_n) - f(x_{n-1}) \quad (1)$$

where $f(x) = 3\text{E}+06x - 6\text{E}+09$, represents the cumulative total annual biomass model (Figure 6), and n and $n-1$ are two consecutive years, respectively.

Since the model is useful for predicting the annual total biomass for years beyond 2010, let n > 2010. For the year n, let T be the number of years beyond 2010. The following equation can be used to predict total annual biomass production, T years after 2010.

$$\begin{aligned}&\text{Total annual biomass production in } 2010+T\\&=\text{Cumulative total annual biomass by } 2010+T\\&\quad-\text{Cummulativetotal annualbiomass by } 2010+(T-1)\end{aligned} \tag{2}$$

To determine the total annual biomass production in 2030, let T = 20. Substitute T = 20 and T − 1 = 29 into Equation (1). The following equation illustrates this operation.

Biomass production in 2030 = Cumulative biomass 2030 − Cummulative biomass 2029.

The total cumulative annual biomass for 2030 and 2029 can be read from the extrapolated model in Figure 6.

Hence, total annual biomass production in 2030 = 96000000 − 80000000 = 16000000 (BDT).

A summary of the regression on analysis generated by Microsoft Excel statistical tool kit is presented in Table 11. R squared was found to be 0.999 with a p-value less than 0.05 (9.65E−15). The regression line represents approximately 100% of the variation in the data and is statistically significant at 0.05 level of significance.

As Table 11 shows, the variation between the total annual cumulative biomass production by Louisiana with respect to years is statistically significant. Louisiana's biomass from logging can be converted to biofuel through processes illustrated in the following concept map (Figure 7).

Table 11. A summary for the regression on analysis for the variation of total annual cumulative biomass versus years.

Regression Statistics								
Multiple R	0.999481							
R Square	0.998963							
Adjusted R Square	0.998847							
Standard Error	15963.34							
Observations	11							
ANOVA								
	Df	**SS**	**MS**	**F**	**Significance F**			
Regression	1	2.21E+12	2.21E+12	8667.605	9.65E−15			
Residual	9	2.29E+09	2.55E+08					
Total	10	2.21E+12						
	Coefficients	**Standard Error**	**t Stat**	**P−value**	**Lower 95%**	**Upper 95%**	**Lower 95.0%**	**Upper 95.0%**
Intercept	−2.8E+08	3051703	−92.8116	9.92E−15	−2.9E+08	−2.8E+08	−2.9E+08	−2.8E+08
Year	141702.3	1522.044	93.09997	9.65E−15	138259.2	145145.4	138259.2	145145.4

8. Potential for Bio-Oil Production in Louisiana

Figure 8 displays Louisiana's oil production and refinery operable capacity from 1900 to 2009. From this figure, it is projected that the capacity of Louisiana to produce oil is likely to reduce after 2009. Following the spike in gasoline prices in 2008, where the state ultimately topped $4 per gallon at the pump, emanating from $140-plus per barrel of oil, there was a rekindled pull to non-fossil or alternative fuels, such as solar, wind, or biomass (energy from forest waste). Mouawad (2009) suggests that oil pricing will be volatile in the future with this trend. Goodstein (2004) argues that based on the "go green" movement coupled with the apocalyptic ruin aligned with those asserting the world would soon run

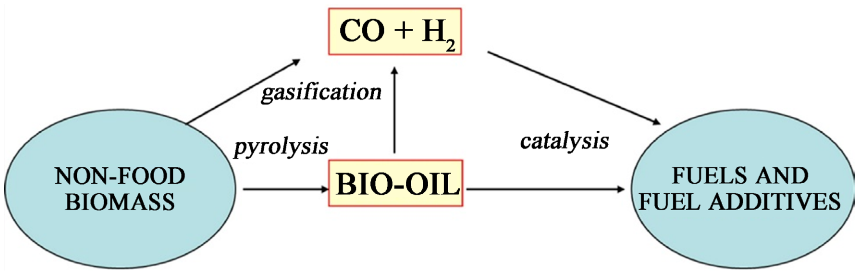

Figure 7. Possible processes for converting biomass to biofuels (Bulushev & Ross, 2011).

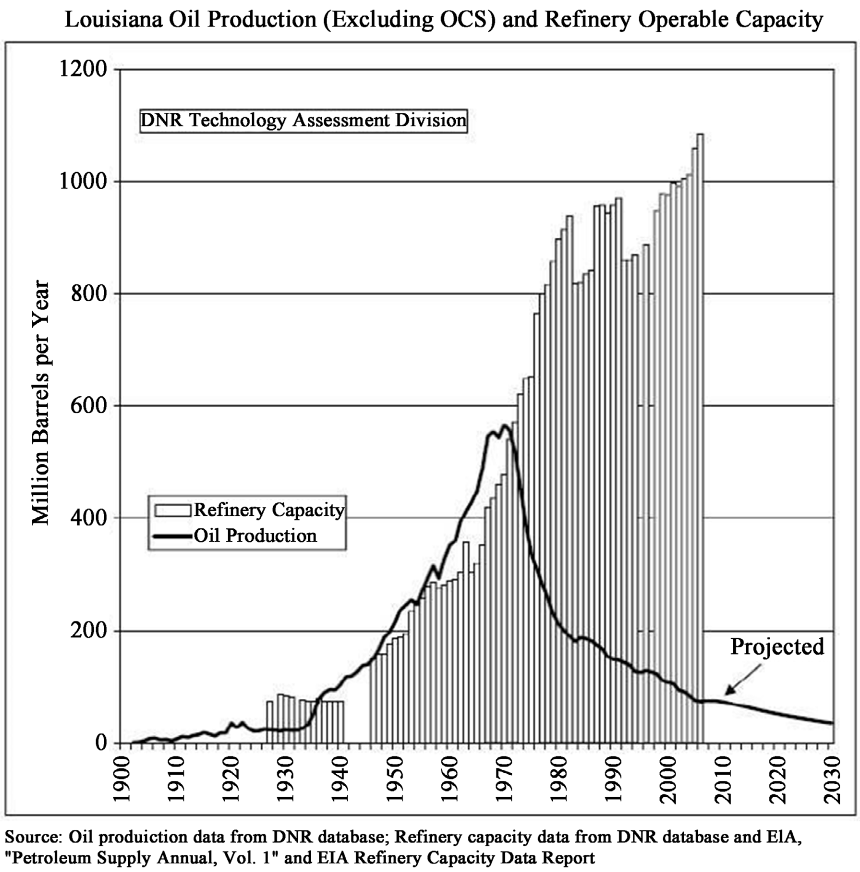

Figure 8. Louisiana Department of Natural Resources, Technology Assessment, Production vs. Refining Capacity (Sutherlin, 2009).

dry, Louisiana would seem to accommodate the new rules of "going green" (Sutherlin, 2009). The argument presented in this paper demonstrates that Louisiana has an immense biomass supply from forest wastes for bioenergy production. Thus, the potential for Louisiana to become a substantial actor in the production of bio-oils from forest residues is prominent. In agreement with Sutherlin (2009), what is lacking is the governance structure together with leadership. With an effective governance structure and leadership, Louisiana can be a hub for bioenergy production in some years to come.

9. Availability of Forest Wastes for Bio-Oil Production in Louisiana

The United States of America is a major producer and consumer of forest products worldwide. Since the mid-1960s, the overall US timber consumption has climbed by 43% in lumber, 32% in plywood, 45% in pulpwood, and 33% in fuelwood. However, from 1965 to 2005, US per capita consumption of wood products remained stable, ranging between 60 and 83 cubic feet per person per year. During this time, production increased by 44%. Currently, the US consumption of forest products is 4.2 billion cubic feet more than the output (Alvarez, 2007). As of now, the country's forest economy supplies more than just timber. Forest biomass leftovers are now accessible in various logging wastes, including unsaleable tiny stems, understory plants, and wood fiber for other goods (e.g., pulpwood). Traditional Roundwood products such as pulpwood, sawmill, and clean pulp chips are already produced in a globally competitive wood supply chain. Wood pellets, bioenergy from wood, and liquid fuels are emerging industries that can use tree biomass which is not already utilized in traditional markets (Greene et al., 2011).

Currently, biomass is the most common home source of renewable energy, with forests accounting for 75% of it (Perlack et al., 2005). Woody biomass may be utilized to generate energy in various ways, such as firewood, pellets, cellulosic ethanol, and as a fuel in co-firing and cogeneration plants. In general, utilizing wood for energy offers the following benefits over coal and other fossil fuels: it is renewable, emits 90% less CO_2, contains few metals and sulfur, produces less ash, and is relatively affordable compared to fossil fuels (Bergman & Zerbe, 2004). According to projections, the United States could produce 10% of its energy from wood, a threefold increase over its current output (Kizhakkepurakkal, 2012). Louisiana is blessed with over 13.8 million acres of forestland. It has been estimated that the waste products obtained after logging operations have been carried out could yield more than three million dry tons of biomass yearly. In this state, bark, sawdust, and other debris, which constitute 98% of the milling residues, are used for energy production (Jackson, 2003).

10. Conclusion

Logging residues, a type of biomass left unwanted after logging, have been approved as a substitute for producing bio-oils in Louisiana. This study estimated the annual potential values of forest wastes based on detailed and existing data on the forest structure in the rural-urban interface in Louisiana and demonstrates the potential of forest wastes to produce bio-oils in the state. The study shows that Louisiana has great potential for producing biomass for energy production in the form of logging residues. It is highly recommended that the state should conduct a cost-benefit analysis for the production of biofuel and compute the opportunity costs for replacing fossil fuels with biofuels and vice versa. There is an extensive spectrum of study in this area. Future studies can use Geographic Information Systems (GIS) to create maps showing the location of production and utilization centers of forest wastes for bioenergy production in Louisiana.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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