Dissertationes Forestales 399

Valorization of non-traditional lignocellulosic feedstocks for bioenergy and biorefinery applications

Nikolaos Papamatthaiakis

School of Forest Sciences
Faculty of Science, Forestry and Technology
University of Eastern Finland

Academic dissertation

To be presented, with the permission of the Faculty of Science, Forestry and Technology of the University of Eastern Finland, for public criticism in the auditorium F100 of the University of Eastern Finland, Yliopistokatu 7, Joensuu, on 9 of October 2026, at 12 o' clock noon.

Title of dissertation: Valorization of non-traditional lignocellulosic feedstocks for bioenergy and biorefinery applications
Author: Nikolaos Papamatthaiakis

Dissertationes Forestales 399
https://doi.org/10.14214/df.399

Thesis Supervisors:
Professor Blas Mola-Yudego (main supervisor)
School of Forest Sciences, University of Eastern Finland, Finland
Professor Antti Haapala
Department of Chemistry, University of Eastern Finland, Finland
Professor Andressa Ribeiro
Department of Forest Engineering, Federal University of Piaui, Brazil
Professor Antonio Carlos Ferraz-Filho
Department of Forest Engineering, Federal University of Piaui, Brazil

Pre-examiners:
Professor Primož Oven
Department of Wood Science and Technology, Biotechnical Faculty, University of Ljubljana, Ljubljana, Slovenia
Professor Bartłomiej Mazela
Laboratory of Wood Preservation and Conservation, Faculty of Wood Technology, University of Life Sciences in Poznań, Poznań, Poland

Opponent:
Associate Professor Sara González-García
Cross-disciplinary Research in Environmental Technologies, University of Santiago de Compostela, Santiago de Compostela, Spain

ISSN 1795-7389 (online)
ISBN 978-951-651-888-9 (pdf)

Publishers:
Finnish Society of Forest Science
Faculty of Agriculture and Forestry of the University of Helsinki
School of Forest Sciences of the University of Eastern Finland

Editorial Office:
Finnish Society of Forest Science,
Viikinkaari 6, FI-00790 Helsinki, Finland
http://www.dissertationesforestales.fi

Papamatthaiakis, N. (2026) Valorization of non-traditional lignocellulosic feedstocks for bioenergy and biorefinery applications. Dissertationes Forestales 399. 58 p. https://doi.org/10.14214/df.399

ABSTRACT

Biomass is considered an abundant renewable resource for energy production through established routes such as combustion, biochemical conversion, and industrial energy systems. These applications could benefit from diversified feedstocks and provide a clear understanding of how different conversion processes influence fuel quality and the potential of side-stream products. Emerging technologies and developing markets may enhance the effective valorization of newly introduced resources, maximize their uses and profitability, and reduce the environmental footprint. At present, comparative data on non-traditional lignocellulosic feedstocks under region-specific conditions are scarce, and such data could further support a better-established acceptance of bioenergy. This thesis evaluates herbaceous perennial energy crops, coffee by-products, and native hardwood species from Brazil, with emphasis on their suitability for bioenergy and biorefinery applications. In **Paper I**, giant knotweed (*Fallopia sachalinensis* var. Igniscum') and Virginia mallow (*Sida hermaphrodita*) were assessed for their capacity for pellet production under Nordic conditions, combining field data and physical and chemical analyses. The results for bulk density, moisture, energy content, and elemental composition were in line with certification schemes, but mechanical durability and ash require further investigation. **Paper II** examined how hydrothermal liquefaction (HTL) could benefit coffee by-products by improving combustion properties and producing chemicals with potential and value-added applications. The hydrochars showed higher energy content than the raw materials, containing chemically complex oil fractions rich in fatty acids and alkaloids. **Paper III** evaluates native hardwood species from the Brazilian Cerrado - Caatinga transition zone, without prior evidence existing about their industrial energy applications. Forest inventory distribution data, dendrometry characteristics, and combustion-relevant fuel property measurements were used to identify species with favorable tree capacity and combustion properties. The thesis provides comparative information on non-traditional biomass resources and conversion routes, suggesting new additions in feedstock portfolios for bioenergy and biorefinery development.

Keywords: Energy crops, hardwood species, coffee by-products, pellets, hydrothermal conversion, chemical compounds, certification

ACKNOWLEDGEMENTS

My deepest thanks to the main supervisor of my thesis, Prof. Blas Mola-Yudego, for proposing that I continue as a PhD researcher, believing in me, and for his constant support, guidance, and understanding throughout my academic journey, both professionally and personally. I would like to truly thank my co-supervisor, Prof. Antti Haapala, for always keeping his office door open, for consulting me on any concerns I had over the years, for trusting my laboratory skills by encouraging me to express new ideas, and for standing on my side when some experiments were not working well. I am grateful to my co-supervisors, Prof. Andressa Ribeiro and Prof. Antonio Carlos Ferraz Filho, for trusting me with their study material, providing the necessary information, and always maintaining positivity.

I am grateful to the School of Forest Sciences of the University of Eastern Finland for opening its doors and providing a cozy place to work and access to the necessary laboratory facilities and equipment, enabling me to learn and become a better researcher. I acknowledge the North Karelia Regional Fund of the Finnish Cultural Foundation, the Liisa and Inkeri Hiltunen Foundation, and the School of Forest Sciences for the financial support, which was a decisive part of starting and completing my doctoral studies, as well as the projects that funded my research work and covered travel expenses.

I am very thankful to Dr. Marja Kolström for introducing me to the bioenergy topic and giving me the chance to start working on it, and to Dr. Lauri Sikanen for his guidance during my first steps in bioenergy research. My papers were made possible by the contribution of my co-authors: Prof. Jänne Janis, Prof. Emeritus Ari Pappinen, DSc. Suvi Kuittinen, and DSc. Aitor Barbero-López, DSc. Eemeli Eronen, MSc. Sara Pineda Zapata, Antti Laine (Research Scientist in Natural Resources Institute Finland – LUKE), and Risto Ikonen (Laboratory technician in the School of Forest Sciences). I managed the main tasks of my research work thanks to the assistance of Maini Mononen, Leena Kuusisto, Jarmo Pennala, and Anssi Kokkonen, as well as Prof. Jukka Tikkanen, Prof. Emeritus Jyrki Kangas, and Iiris Korhonen, who facilitated the necessary processes for renewing the agreements with the School of Forest Sciences. I want to express my appreciation to the pre-examiners, Prof. Primož Oven and Prof. Bartłomiej Mazela**,** for accepting the request to review this thesis and for their time commenting on and supporting the completion of the last stages of my studies. In addition, I am honored that Assoc. Prof. Sara González-García agreed to be the opponent for the public examination of my doctoral dissertation.

During my studies, my supervisors offered me the opportunity to teach and supervise, an experience that helped me better understand and learn many things, thanks to the students with whom I interacted and the useful questions, comments, and feedback they provided. My colleagues, as well as office and laboratory mates, Marina, Aitor, Sara, Mari, Xin, Qianqian, Daniela, Xiaoqian, Jaka, Eija, Heli, Isabel, Marta, Nina, Yeray, Philip, Carlos, Carlos, Karen, Sergio, Olalla, Vijay, Prof. Henrik Heräjärvi and DSc. Marjorritta Möttönen, whom I had the honour of meeting during these years. Thank you all for tolerating me, being an example to me, never giving up on supporting me, pushing me forward, and for your kindness all these years.

In my personal life, my friends and important people to my life father Vasileios, Stylianos, Argyris and Sirmo, father Ioannis and Riika, Anastasis and Iiris, my godmother Evangelia, Foteini, Pantelis and Anastasia, Jukka and Minna, father Joonas and Valeria, father Tuomas and Tuula, father Aleksander and Maria, father Marko and Tea, father Nemanja and Elisa, father Kalevi, Petri and Kaisa, Michael and Anna-Lissa, Julian and Daniela, Panu and Tuire, Tuuli, Mikal, Harri, Pekka, Kaisa, Petri, and all the people that I might forget, I am still here pursuing my dreams because of having you in my life believing in me, no matter the mistakes I do.

My true love, my beautiful wife, Charikleia; my hero, my son, Iosif; my princess, my daughter, Christina. I am very sorry for all the difficulties you have endured over the past years. I am more than grateful for your love and support, tears, efforts, waiting, warm home and tasty food, big hugs and caresses, sweet words, and much more, which I simply cannot put into words. I thank my beloved, supportive, and good parents, Iosif and Angeliki; my good brother, Apostolos, and his family, Elli and Iosif; as well as my parents-in-law, Ilia and Christina, and my siblings-in-law, for being present in my life and loving me.

I am Christian Orthodox, and I believe in God. Nothing would have happened without God being present in my life. I thank God, Most Holy Theotokos and Ever-Virgin Maria, and Saint Nikolaos for gracing my life with a family, fine people, and opportunities I had never dreamed of; guiding every step of my life, even when I was not realizing it, giving me strength, and allowing me to continue on the right path and to try for the good each time.

Joensuu, 15th May, 2026

Nikolaos Papamatthaiakis

LIST OF ORIGINAL ARTICLES

This thesis is based on data presented in the following articles, referred to by the Roman Numerals I-III.

I Papamatthaiakis N, Laine A, Haapala A, Ikonen R, Kuittinen S, Pappinen A, Kolström M, Mola-Yudego B (2021) New energy crop alternatives for northern Europe: Yield, chemical and physical properties of Giant knotweed (*Fallopia sachalinensis* var. 'Igniscum') and Virginia mallow (*Sida hermaphrodita*). Fuel 304, article id 121349. https://doi.org/10.1016/j.fuel.2021.121349

II Papamatthaiakis N, Barbero-López A, Eronen E, Jänne J, Mola-Yudego B, Haapala A (2025) Hydrothermal Liquefaction of Coffee Silverskin and Spent Coffee Grounds: Bioenergy and Biochemical Potential. BioEnerg. Res. 18, article id 65 https://doi.org/10.1007/s12155-025-10867-3

III Papamatthaiakis N, Ribeiro A, Pineda Zapata S, Ferraz Filho AC, Haapala A, Mola-Yudego B Insights into the combustion properties and forest traits of native wood species for the emerging bioeconomy in NE Brazil. Manuscript.

Nikolaos Papamatthaiakis was the principal author of all articles, responsible for conceptualization, experimental design, sample preparation, laboratory analyses, data compilation, and writing, reviewing, and editing of all the manuscripts. Co-authors participated in the planning of the studies, conceptualization, experimental design, delivery of study materials, writing, reviewing, and editing of the manuscripts, and supervision.

LIST OF ABBREVIATIONS

ASP	*Aspidosperma pyrifolium*
BA-R	Baqué silverskin raw
BA-HC	Baqué silverskin hydrochar
BD	Bulk density
CAV	*Campomanesia velutina*
CAM	*Callisthene minor*
CEM	*Cenostigma macrophyllum*
COG	*Combretum glaucocarpum*
COL	*Copaifera luetzelburgii*
COT	*Cordia toqueve*
DAC	*Dalbergia cearensis*
DMC	Dry matter content
DMY	Dry matter yield
DU	Mechanical durability
DUM	*Duguetia marcgraviana*
FC	Fixed carbon
FWY	Fresh weight yield
GCV	Gross Calorific Value
HTC	Hydrothermal Carbonization
HTG	Hydrothermal Gasification
HTL	Hydrothermal Liquefaction
HYM	*Hymenaea martiana*
LUP	*Luehea paniculata*
MA-R	Mariposa silverskin raw
MA-HC	Mariposa silverskin hydrochar
ME-R	Meira silverskin raw
ME-HC	Meira silverskin hydrochar
MYT	*Myrcia tomentosa*
NCV	Net Calorific Value
NFI	National Forest Inventory
PIM	*Pityrocarpa moniliformis*
PTP/PTE	*Pterodon polygalaeflorus*/*Pterodon emarginatus*
SET	*Senegalia tenuifolia*
SC-R	Spent coffee raw
SC-HC	Spent coffee hydrochar
SWF	*Swartzia flaemingii* Raddi
VM	Volatile Matter

TABLE OF CONTENTS

INTRODUCTION

The transition away from fossil-based energy and materials requires not only expanding renewable energy and materials but also a more efficient use of biomass across integrated value chains. In this context, biomass should not be regarded solely as a fuel, but as a versatile raw material that can support the production of energy, chemicals, and other biobased products. Such an approach is closely linked to the development of a circular bioeconomy, in which residual streams, underutilized feedstocks, and regionally available resources are valued to increase resource efficiency and reduce environmental burdens.

However, biomass is not a homogeneous resource. Its physical, chemical, and logistical characteristics vary widely depending on origin, species, plant component, and processing history. These differences strongly influence the suitability of biomass for specific end uses, including direct combustion, densified solid fuels, and thermochemical or biochemical conversion routes. As a result, the identification and assessment of alternative biomass feedstocks have become an important research priority, particularly when conventional raw materials are limited, contested, or raise sustainability concerns. Thus, adding new knowledge will increase the flexibility for effective use of biomass and support the incorporation of versatile processing with a larger number of feedstocks.

Within this framework, the present thesis examines the potential of selected non-traditional lignocellulosic feedstocks for bioenergy and biorefinery applications. By addressing herbaceous perennial crops, coffee by-products, and native tropical hardwood species, the thesis contributes to the broader discussion on how diverse biomass resources may support renewable energy production, industrial valorization, and regional bioeconomy development.

Alternative biomass feedstocks for mitigating fossil fuels dependence

Biomass is an important renewable resource for heat and energy production. For instance, wood-derived biomass has traditionally been used to produce thermal energy. Nevertheless, this does not constitute bioenergy as such. Bioenergy is directly linked to advanced, sustainable uses of biomass, whether lignocellulosic or non-lignocellulosic. To be more precise, bioenergy involves converting biomass via diverse pathways, such as biochemical and thermochemical methods, to produce more efficient, value-added products (Bose et al. 2022; Chaudhary et al. 2025). That enables the production of biofuels, and solid densified fuels with high energy content, and chemicals. In terms of lignocellulosic biomass feedstocks, these include forest and agricultural residues, dedicated energy crops, industrial by-products, and waste (IEA 2024d).

Sustainably derived biomass does not add carbon when used for energy compared to fossil fuels, helping mitigate the consequences of climate change and reduce greenhouse gas (GHG) emissions. In addition, sustainability encompasses characteristics such as economic expediency, controlled environmental footprints, and social impacts (Özdenkçi et al. 2017; Kardung et al. 2021). Biobased feedstocks are a considerable solution for substituting petroleum-based chemical products (Tsakalova et al. 2024). Biomass resources could also support energy autarky and reduce the need to import energy supplies (Ericsson and Nilson 2006; Frombo et al. 2009; Balcioglu et al. 2023). On the other hand, progress of technologies related to other renewable resources, and the status of other primary energy sources are factors challenging the potential of biomass for energy applications (Berndes et al. 2003).

The basis of the lignocellulosic biomass is the contained components: cellulose, hemicellulose, and lignin. These components can be detected in different analogies, depending on the material origin (wood or herbaceous), species, and tissue type (wood, bark, roots, leaves, needles). Apart from that, other factors can also impact this variation, such as age, climatic conditions, and storage processes (Bhatia et al. 2020). This diversified composition plays a role in processing and the properties of the final products. For instance, bark pellets release similar amounts of energy to those from sawdust, but their ash content is much higher, and longer storage periods are also associated with higher ash content (Lehtikangas 2001). Thus, it is important to have as much information as possible about the composition and properties that will be linked to advanced and sustainable uses (Vassilev et al. 2012). In this regard, assessing biomass feedstocks with different origins could provide valuable insights into how they could fit into energy production.

Even though most biomass resources have potential for bioenergy and biorefinery, the decision of which resources to use should be carefully made. Controversies have arisen over the share of arable land to be allocated for crop plantations for energy purposes. Similarly, the use of food crops to produce biofuels, also known as 1st-generation biofuels, has occasionally drawn criticism for using biomass for energy. To tackle these issues, 2nd-generation biofuels were developed based on non-edible feedstocks, also known as dedicated crops for energy applications (Rafael et al. 2008). Optimizing the use of biomass residues could further enhance the development of a bio-based circular economy (Muscat et al. 2021).

Biomass for energy production could boost local economies, and it is a well-established concept with many notable examples. In Germany, the contribution of biomass to energy generation increased from 1.8% in 2005 to 7.7% in 2022 (AGEB 2023). In 2022, bioenergy accounted for 13.93 TW of power production, ranking second after nuclear power in Finland, and solid biomass was used to produce 10.08 Mtoe of primary energy in Sweden (Ember 2023; EurObserv'ER 2024a). In Greece, biogas production amounted to 145.3 ktoe in 2022, compared with 127.2 ktoe the previous year (EurObserv'ER 2024b). The use of regional biomass feedstocks is important for achieving this, as it minimizes emissions across the transportation stages (The Royal Society 2008). In addition, transporting feedstocks with low moisture content also benefits the supply chain by reducing costs (Tahvanainen and Anttila 2011). Setting standards as part of certification schemes strongly provides the necessary tools for validating biofuel characteristics alongside the related production and trade processes (Lewandowski and Faaij 2006).

Bioenergy in Nordic countries

Biomass, especially derived from forest residues, plays a significant role in strategies to increase energy production in Nordic countries (Cross et al. 2021). Several factors limit the margin for increasing forest biomass production. For instance, there will be a need to intensify forest management while minimizing negative environmental and social impacts (Bostedt et al. 2015). In addition, commercialization factors and technological development among others will shape the available feedstocks (Trømborg and Solberg 2010). Bioenergy has an important share among the renewable resources in Finland and Sweden. In Finland, biomass accounts for 38% of overall final energy consumption, while in Sweden it accounts for 38.7% (IEA 2024b; IEA 2024c). The development of policies shifting towards to a nonfossil independence is part of the national strategy of Finland. Wood-based energy could play a substantial role in a new era of lower carbon emissions and an increasing share among renewable resources. On the other hand, certain schemes need to be followed to secure a sustainable supply chain and the continuous availability of feedstocks (Ministry of Economic Affairs and Employment of Finland 2022).

Energy cultivations have been established in Northern Europe, offering alternative energy sources. Willow plantation is the dominant species among wood crops for energy, with Sweden leading in reported plantations (Larsson and Lindegaard 2003; Mola-Yudego and González-Olabarria 2010). Denmark was a pioneer in establishing *Miscanthus* spp. plantations for pulp and energy applications at the end of the 1960s, with willow cultivations being introduced in the following years (Venendaal et al. 1997; Cahyanti et al. 2020). The use of wood chips for producing heat and energy is the most common practice in Finland. So far, there are limited efforts to establish energy crops, even though there is potential without threatening food and feed crop production (Finnish Ministry of Agriculture and Forestry 2005; Rämö et al. 2009). Reed canary grass (*Phalaris arundinacea* L.) showed the most promising results among the tested species, withstanding the harsh winter condition in Finland (Venendaal et al. 1997). A case study in Ostrobothnia, Finland, resulted an increase in reed canary grass areas, from 18 ha to 2300 ha for the period 2002-2006 (Pahkala et al. 2008)

Even though energy crops were accepted to a certain extent by farmers, bottlenecks limited the transition from trial-scale to full commercialization, such as the lack of supportive policies and ongoing subsidies (Venendaal et al. 1997). In Sweden, low yields of willow negatively influenced the interest for new farmers to adopt short rotation coppice plantations (Dimitriou et al. 2011). Even with well-designed subsidies, a group of landowners will remain skeptical about accepting energy crops on their own property, rendering it challenging to achieve widespread acceptance (Soliño et al. 2018). In addition, uncertainties in the prices of goods, challenges in energy markets, and a lack of commercial-driven institutional frameworks obscure the potential for farmers to adopt energy crop production. (Ostwald et al. 2013; Streimikiene et al. 2021; Thomson Ek et al. 2024).

Nordic conditions are characterized by short growing seasons and low temperatures, which hamper crop growth and play a role in yield productivity. Therefore, prospective energy crops should possess characteristics that enable them to withstand these harsh conditions. In addition, these crops should demonstrate successful growth in low-quality soil, as the most productive areas are intended for food production, and low dependence on water supply. Regarding the combustion characteristics of energy crops, they should have high energy content and low ash, and elements such as chlorine (Cl) and sulfur (S) should not exceed the suggested thresholds. Regarding herbaceous crops, which contain less lignin than woody crops, the mechanical durability of densified fuels is expected to be affected (Tumuluru 2018). In addition, pellets derived from herbaceous crops tend to have higher ash content (Stolarski et al. 2025).

Pellet consumption totaled 33 million tons in Europe in 2024, with about 30% imported (Bioenergy Europe 2025). Germany and Austria lead the list of the certified pellet-producing countries, followed by France, Spain, and Poland (ENplus® 2025). The corresponding figure for Finland was 536 000 tons, an increase of 9% compared to the previous year (Natural Resources Institute Finland 2025). Finland imported 213 000 tons of pellets from the Baltic countries and Denmark to meet consumption needs (Natural Resources Institute Finland 2025). Although pellet consumption in Finland is not as popular as in other countries, there is ongoing progress towards greater acceptance among new users (Selkimäki et al. 2010; Proskurina et al. 2017).

The demand and prices of wood pellets are affected by geopolitical factors, limited availability of raw materials, and environmental disturbances, highlight the importance of research for new feedstocks (Selkimäki et al. 2010; Magiera et al. 2025; Pinho et al. 2025). Studying new crops could broaden the available feedstock options, providing alternatives based on regional factors. Moreover, suitable candidates should demonstrate good yield productivity and combustion properties and contain harmful chemical elements below the recommended thresholds.

Hydrothermal conversions of coffee by-products

The demand for biomass feedstock is growing steadily, both for energy production, material development, and chemical extraction. As a result, competition will arise between different biomass feedstocks, edible or not, and between the best-suited use in each case (Gerssen-Gondelach et al. 2014). Seeking new alternatives could expand the feedstock portfolio and help address forthcoming issues. Organic residues and by-products are among these alternatives, as they can be found in a wide range of production activities, including food production, forest management, and processing agricultural products. It is worth mentioning that sustainable valorization of residues could alleviate the shortage of feedstocks and limiting adverse ecological impacts (Cherubini et al. 2009). Valorizing waste side-streams could yield revenue for stakeholders and provide effective waste management, promoting circularity (Haldar et al. 2022; Remijnse et al. 2025).

Coffee silverskin is a thin layer of skin that encloses each of the two coffee beans in a coffee cherry (Saenger et al. 2001; Narita and Inouye 2014). Silverskin is the final by-product remaining after the roasting process, mainly deriving from Robusta coffee than Arabica (Zoccatelli and Ciulu 2025). Spent coffee grounds are the remaining wastes of the brewing process. It is estimated that 1 kg of instant coffee produces 2 kg of spent coffee grounds (Pfluger 1975). Current disposal methods of spent coffee grounds include soil amendment, bioenergy feedstock, and as substrate for mushroom production (Campos-Vega et al. 2015). Silverskin and spent coffee grounds can consist of about 24% and 12% cellulose, 17% and 39% hemicellulose, and 29% and 24% lignin, respectively (Ballesteros et al. 2014). Silverskin contains antioxidant compounds with phenolics, caffeine, and melanoidins being the most representative (Bessada et al. 2018a). Some studies have reported potential uses from valorizing silverskin, such as a functional ingredient in food products and as a fiber and mineral resource (Bessada et al. 2018b; Zoccatelli and Ciulu 2025). Spent coffee grounds could be, for instance, a source for biofuel production and extraction of substances for commercial use (Mussato et al. 2012; Zhao et al. 2024).

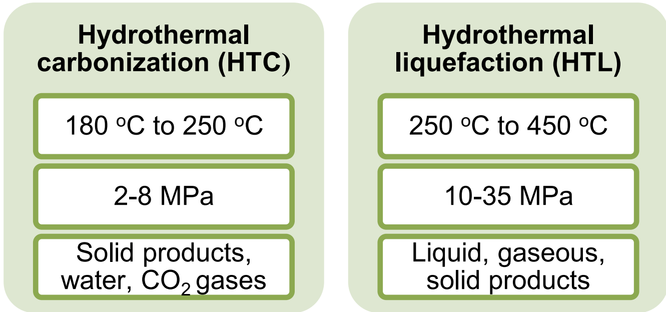

Figure 1. Differences between hydrothermal carbonization (HTC) and hydrothermal liquefaction (HTL) include temperature and pressure settings and the types of primary products produced by the processes.

The main methods of thermal conversion of biomass are combustion, gasification, pyrolysis, and hydrothermal (Luo and Zhou 2025). Processing by-products, and residues through thermal conversion could improve their management and enhance circularity (Dussan and Monaghan 2018; Leon et al. 2018; Shen et al. 2025). Hydrothermal processing encompasses hydrothermal carbonization (HTC), hydrothermal liquefaction (HTL), and hydrothermal gasification (HTG) (Ruiz et al. 2021). More specifically, HTC takes place in lower temperatures and pressure, 180 ºC - 250 ºC, and 2-8 MPa, respectively, with the corresponding values for HTL being 250 ºC - 450 ºC, and 10-35 MPa (Funke and Ziegler 2010; Castello et al. 2018; Heidari et al. 2019; Harisankar et al. 2022; Lachos-Perez et al. 2022). These differences between HTC and HTL are the processing temperatures and the obtained products (see **Fig. 1**). Mainly solid char, also known as hydrochar or biochar, the added water-with some biomass contained particles, CO_2 gas fractions can be obtained at the end of the HTC process, whereas HTL produces insoluble and soluble organic liquids, gases, and a solid slurry (Ruiz et al. 2021; Lachos-Perez et al. 2022). A key benefit of hydrothermal methods is that wet biomass can be processed without prior drying (Vardon et al. 2012; Anastasakis et al. 2018; Hedayati Marzbali et al. 2021). In addition, water can also be used as a solvent during the reaction, providing cost-effective and environmentally sustainable features for the process (Kiran Kumar et al. 2018).

In recent years, research on biomass valorization through hydrothermal conversion has increased rapidly, especially in the advanced treatment of residues and waste materials (González-Arias et al. 2022; Fan et al. 2023). A solid product derived from HTL treatment of sewage sludge showed certain levels of removal of dye agents from aqueous solutions (Leng et al. 2015). Wastewater from algae cultivation could be considered as a feedstock for biofuel production with applied HTL (Silva et al. 2024). Biomass feedstocks transported with water-based systems were investigated for HTL-produced biocrude (Mohan et al. 2025). Catechols and phenols were detected in wood bark and hemp hurds derived from HTL liquids, indicating source for diverse applications in the chemical industry (Jokinen et al. 2023).

Native species for boosting regional economy and strengthening biodiversity

Brazil has a well-established biofuel industry, with bioenergy experiencing steady growth over the past 20 years (IEA 2021). Ethanol and biodiesel report the highest production, followed by solid biomass fuels (IEA 2024a). Ethanol from sugarcane is mainly used for domestic transportation, with exports accounting for a smaller share (USDA 2023). Wood residues and by-products, whether from forest management practices or industrial processing, represent vast quantities of feedstock for producing electrical power in combined heat and power plants (IEA 2024a). Brazil is the largest charcoal producer in global scale, with 6.7 million tons being used annually in domestic level from 2021 to 2024 (IBÁ 2025). About 73% of wood biomass from native species was used to produce charcoal and firewood in 2005 (Ferreira-Leitão et al. 2010).

The Brazilian Cerrado (hereafter referred to as "Cerrado") and Caatinga biome span approximately 2.8 million km^2, occupying 23.3% and 10.1% of the national territory, respectively (IBGE 2019). The Cerrado biome, the second largest after the Amazon, has a complex vegetation system including grasslands, shrublands, savanna forests, and agricultural lands (Ribeiro and Rodrigues 2006; Sano et al. 2007; Aguiar et al. 2015). The flora of the Cerrado is not that well studied, although the Cerrado is described as a hotspot of biodiversity (Myers et al. 2000; Simon et al. 2009). The Caatinga biome, on the other hand, has characteristic xerophytic, thorny shrub vegetation, with scattered clusters of tall dry forests or humid forests (Andrade-Lima 1982; Prado 2003; Leal et al. 2005).

Over the past 40 years, a notable reduction in native vegetation has been recorded in the Cerrado biome, while the land share for pastures and growing crops has increased (MapBiomas 2025). Growth in the number of soybean plantations has been recorded in Cerrado since 2000 (Severo dos Santos and Naval 2022). In the Amazon rainforest, 80% of private properties in rural regions should be reserved as protected areas, according to national legislation, whereas in the Cerrado biome, it is 20% and 35% for Cerrado-Amazon overlapping zones of the biomes (Strand et al. 2018; Rajão et al. 2020). The biodiversity status of the Caatinga biome has not been extensively studied compared to other regions of the country, and land cover change monitoring is lacking (Santos et al. 2011; Beuchle et al. 2015). The flora of Caatinga includes endangered species in high risk and an increasing number of newly discovered species (Fernandes et al. 2020)

Production of firewood has strong roots in northeastern Brazil, accounting for 21.3% of annual production in 2016 (Coelho Junior et al. 2019; Oliveira et al. 2023). Firewood production plays an important role at the social level, used for heating, but illegal logging rates are high (Coelho Junior et al. 2019). The area where most of the species studied in **Paper III** were collected is used to extract wood energy (Nazareno et al. 2021). Developing legislation for environmental sustainability has previously helped implement forest management practices for charcoal production (Bichel and Telles 2021). Apart from applying legislation, local communities need to be better informed about uncontrolled exploitation to minimize future disturbances (Souza et al. 2018). Besides vegetation loss, there is also a high risk of soil degradation, water security, biodiversity loss, and, subsequently, a negative impact on the livelihoods of local communities (Qiu et al. 2018; Ribeiro et al. 2021).

Utilizing biomass feedstocks poses challenges, as stakeholders must properly address several intermediate steps. Thus, a tailored approach is needed to achieve the greatest benefits by securing high-quality products and services within a sustainable framework. Though the aim is energy output, guidance through certification schemes and an underlying understanding of how to improve the properties are indispensable, especially for an emerging economy such as Brazil.

Aims of the thesis

The present thesis aims to address the valorization of three types of lignocellulosic biomass, such as herbaceous biomass, coffee by-products, and wood, as alternative renewable feedstocks for bioenergy and biorefinery uses. To support a comprehensive assessment of the studied material, complementary parameters are presented and linked to field data, as well as to physical and chemical properties. In addition, an evaluation based on certification schemes clarifies potential barriers. Thus, the results summarize both quantitative and qualitative characteristics that support decision-making in a supply chain and increase the likelihood of better alignment with a bioeconomy concept.

Objectives

This dissertation has the main objectives:

i) To investigate new energy crops as a biomass resource for pelletizing in Finland, by checking productivity, mechanical characteristics, and chemical properties.
ii) To check how hydrothermal processing can elevate the properties of coffee by-products and residues, both for producing biomass fuels and for extracting chemical compounds.
iii) To assess native tropical hardwood species with minimal industrial use, which could enhance as an incentive to boost local economies and advance forest management practices.

The hypotheses are:

1) The combustion-relevant properties of the two energy crops, giant knotweed and Virginia mallow, meet ISO and ENplus thresholds, suggesting a newly introduced feedstock for commercial pellet production.
2) Hydrothermal liquefaction leverages the energy density of coffee by-products and residues, reduces ash content relative to raw materials, and supports chemical extraction.
3) Selected native tropical hardwood species demonstrate robust properties for energy generation within certification limits, initiating a regional resource for incorporation within a bioeconomy plan.

MATERIAL AND METHODS

Materials

Three biomass types were assessed in the present thesis, including crops, coffee production and consumption by-products, and native tropical hardwood species (wood and bark). In **Paper I**, the herbaceous energy crops giant knotweed (*Fallopia sachalinensis* var. 'Igniscum') and Virginia mallow (*Sida hermaphrodita*), both perennials, were investigated as possible feedstock for pellet production in Finland (**Paper I**). The species giant knotweed var. 'Igniscum' originates from the Japanese knotweed Fallopia sp or Mexican bamboo/round knotweed, being detected in Germany (Rogmans 2010). The tested variety developed through natural mutations, without genetic modifications or crossbreeding, and is noninvasive compared to the original one (Seppälä et al. 2013). Virginia mallow is a member of the Malvaceae family, is listed as endangered, and has a natural distribution in the eastern United States and Canada (Bickerton 2011; NatureServe 2021). The trials were established in the former MTT Agrifood Research Finland in Piikkiö (currently, Natural Resources Institute Finland), in southern Finland, in 2010 for giant knotweed and in 2011 for Virginia mallow, consisting of plots of 10 m^2. The harvested crop stalks for the pellet production were stored outdoors, protected from rain and sun and not in contact with the ground (see **Fig. 1**).

Coffee silverskin and spent coffee grounds were two biomass types investigated in **Paper II**. The samples were compressed, provided by Baqué S.L. (Spain), pellets, by Meira Ltd. (Finland), and untreated, by Mariposa Coffee Roasters (Slovenia), with all of them being considered as waste by-products from the places where they were collected (see **Fig. 1**). The spent coffee grounds were collected after coffee making in the premises of the School of Forest Sciences, Joensuu.

In **Paper III**, we evaluated 16 native tropical hardwood species collected from Piauí state, located in northeastern of Brazil, for which there were a few previous studies on chemical properties (**Fig. 2**). The species selection was based on local availability in the transition zone between the Cerrado and Caatinga biomes. Most of the collected samples were from the Aracajú Farm in the municipality of Santa Luz, and one species was collected in an area near the municipality of Colônia do Gurguéia (**Table 1**). The samples from the Aracajú Farm were derived from a harvested area of 2.7 km^2 where approved forest management plan was applied, being designated as a Sustainable Forest Management Plan area (Nazareno et al. 2021).

Figure 1. Example of biomass types analyzed. Top: Harvested stalks of giant knotweed (*Fallopia sachalinensis* var. Igniscum') and Virginia mallow (*Sida hermaphrodita*). Below: Untreated coffee silverskin (left), compressed (center), and in pellets (right).

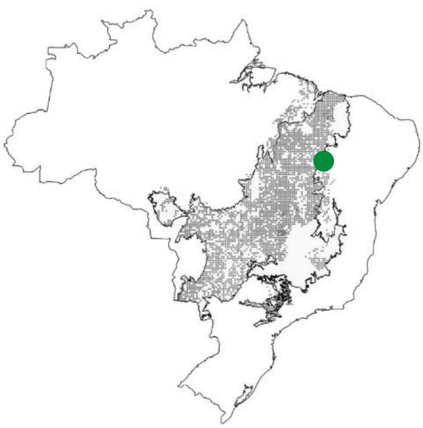

Figure 2. National Forest Inventory (NFI) plots in the *Cerrado* biome (SFB, 2023) and sampling area. The harvested samples were derived from the Aracajú Farm, municipality of Santa Luz, and near the municipality of Colônia do Gurguéia, in Piaui, Brazil.

Table 1. Collected native species, family taxonomy, and area where the samples were collected from.

Species	Family	Collected area
Aspidosperma pyrifolium Mart. (**ASP**)	Apocynaceae	Aracajú Farm
Callisthene minor Mart. (**CAM**)	Vochysiaceae	Colônia do Gurguéia
Campomanesia velutina (Cambess.) O. Berg (**CAV**)	Myrtaceae	Aracajú Farm
Cenostigma macrophyllum Tul. (**CEM**)	Fabaceae	Aracajú Farm
Combretum glaucocarpum Mart. (**COG**)	Combretaceae	Aracajú Farm
Copaifera luetzelburgii Harms (**COL**)	Fabaceae	Aracajú Farm
Cordia toqueve Aubl. (**COT**)	Boraginaceae	Aracajú Farm
Dalbergia cearensis Ducke (**DAC**)	Fabaceae	Aracajú Farm
Duguetia marcgraviana Mart. (**DUM**)	Annonaceae	Aracajú Farm
Hymenaea martiana Hayne (**HYM**)	Fabaceae	Aracajú Farm
Luehea paniculata Mart. (**LUP**)	Malvaceae	Aracajú Farm
Myrcia tomentosa (Aubl.) DC. (**MYT**)	Myrtaceae	Aracajú Farm
Pityrocarpa moniliformis (Benth.) Luckow & R.W. Jobson (**PIM**)	Fabaceae	Aracajú Farm
Pterodon polygalaeflorus Benth. / *Pterodon emarginatus* Vogel (**PTP**)	Fabaceae	Aracajú Farm
Senegalia tenuifolia (L.) Britton & Rose (**SET**)	Fabaceae	Aracajú Farm
Swartzia flaemingii Raddi (**SWF**)	Fabaceae	Aracajú Farm

Methods

The climatic data in **Paper I** were recorded by the Finnish Meteorological Institute from the Kaarina Yltöinen observation station, including monthly minimum and maximum temperatures, rainfall totals, and the effective sum over 5 °C. Soil analyses were carried out for **Papers I** and **III**. The Eurofins laboratories delivered the analysis results for the samples from the areas where the energy crops were cultivated (**Paper I**). As these were experimental trials, reporting the soil characteristics could serve as a reference point in conjunction with yield productivity for future studies. Better knowledge of soil conditions enables more effective management, for instance, by adding sufficient fertilizers to support crop production, achieve high productivity, and prevent disturbances. Soil samples from the Aracajú Farm were also collected and analyzed (**Paper III**). As the wood samples were derived from a stand undergoing natural regeneration management, soil description provides a comprehensive understanding of the favorable ecological conditions for the selected species. The main aspects described in both soil analyses were pH, topsoil characterization, and elemental content. The data obtained for yield productivity, including dry matter content (DMC), and fresh (FWY) and dry mass yields (DMY) (**Paper I**), with the harvested parts of the crop being either stems, leaves, or both stems and leaves. The crops were harvested within three years, either April, May, June (early harvest) or July, August, September (late harvest) from 2012 to 2014, for giant knotweed, and two years, from 2013 to 2014, for Virginia mallow. The fertilizers applied during crop cultivation in the trials were nitrogen (N), phosphorus (P), and potassium (K).

The stalks required pretreatment to enable pelletization and ensure even product quality (**Paper I**). Stalk comminution was achieved using an MTD 5HP woodchipper/shredder (MTD Products LLC, Cleveland, OH, USA). The treated material was forwarded to a hammer mill (Miller 20, Miller s.r.l., San Giorgio in Bosco, Italy), using an 8 mm screen (see **Fig. 3**). The produced hammered material was 107.3 kg for giant knotweed and 23.1 kg for Virginia mallow. The hammered material was finally processed for pelletizing using a pellet press (Type PP330, Sweden Power Chippers AB, Borås, Sweden) with an 8/50 die. The maximum observed temperatures during the pellet production were 95 ºC for giant knotweed, and 78 ºC for Virginia mallow, and the hourly production was approximately 82 kg. Water was constantly added through the chipper moisturizing system to enhance pellet formation. Pelletizing yielded 77 kg of pellets for giant knotweed and 16 kg for Virginia mallow. The obtained biomass of giant knotweed after every process, stalk pretreatment, hammering, and pellet production, can be seen in **Fig. 3**.

The hydrothermal liquefaction (HTL) was carried out with the use of a using a Parr 4580 high-pressure reactor (Parr Instrument Company, Moline, USA), maximum volume of the reactor 5.5 liters, maximum operating temperature at 500 °C, and maximum operating pressure of 250 bar (see. **Fig. 4**). The process included adding 5% of dry feedstock and 95% of water, being set between 94 and 97 bars and 300 °C, with the process duration being 60 min (**Paper II**). This temperature was chosen for delivering adequate volumes of both oils and hydrochar, consistent with prior optimization studies on lignocellulosic residues (Barbero-López et al. 2024; Jokinen et al. 2024). After the hydrothermal conversion was completed, a separation process followed, isolating the solid hydrochar from the water-rich light oil solution.

Both the distribution and the dendrometry characteristics, such as the mean values of total height and diameter at breast height, were obtained from the National Forest Inventory (NFI) of Brazil, which coordinated by the Brazilian Forest Service (SFB 2023) (**Paper III**). These two metrics constitute the basis for the tree volume estimation. The data recorded during 2017-2018, and the maps used to create the figures were retrieved from Natural Earth and the Brazilian Institute of Geography and Statistics (IBGE 2006).

Figure 3. Hammer mill (Miller 20, Miller s.r.l., San Giorgio in Bosco, Italy) used for the hammering process of the giant knotweed and Virginia mallow stalks. Obtained biomass of giant knotweed after pretreatment of stalks (left), hammering process (center), and pellet production (right).

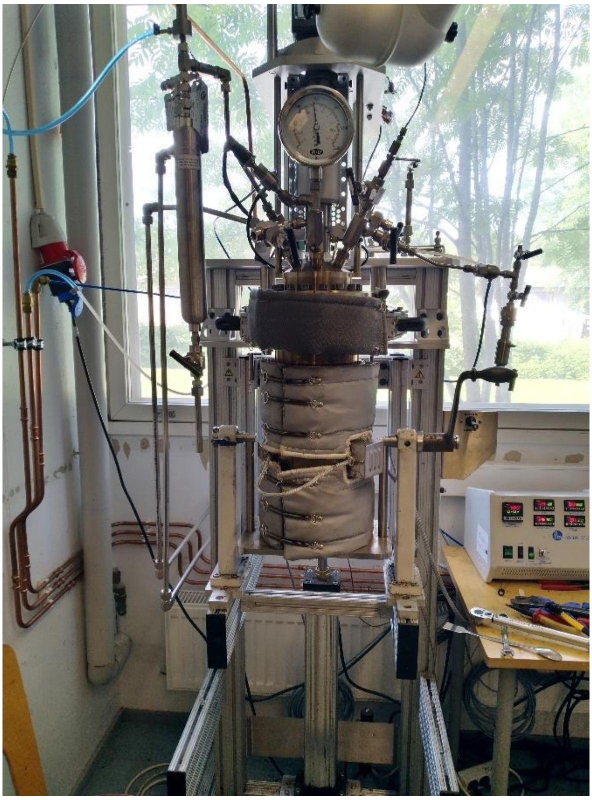

Figure 4. The hydrothermal liquefaction (HTL) Parr 4580 high-pressure reactor at the lab of the School of Forest Sciences, University of Eastern Finland.

The bulk density (BD) was calculated using a 5-liter measuring cylinder. The mechanical durability was calculated using a tumbler with a set rotation speed of 50 rpm and a 10 min rotation time. Equations (1) and (2) were used for the calculations of BD and DU (European Pellet Council 2013):

$$BD = \frac{(m_2 - m_1)}{V} \tag{1}$$

where BD: Bulk Density ($kg \cdot m^{-3}$)
m_1: mass of the empty measuring cylinder (kg)
m_2: mass of the full measuring cylinder (kg)
V: net volume of the measuring cylinder (m^3)

$$DU = \frac{m_A}{m_E} \times 100 \tag{2}$$

where DU: mechanical durability (%)
m_E: mass of wood pellets, not sieved, before testing (kg)
m_A: mass of the wood pellets, sieved, after testing (kg)

A sample of 300 pellets, random selection, was used for each crop for measuring the dimensions of the pellets, and the moisture content was determined by oven dry method at 105°C for 24 h, using an oven Termarks Type TS-5410 following the EN 14774-1:2009 standards, and a moisture analyzer (Radwag MAC 210/NH) (European Committee for Standardization Solid Biofuels 2009). The energy content, gross calorific value (GCV), of the pellets using a bomb calorimeter (EN ISO 1716 Bomb Calorimeter, Fire Testing Technology Ltd, UK) according to ISO 1716:2010 (ISO 2010) (**Paper I**). A static jacket oxygen bomb calorimeter, IKA C1 (IKA-Werke GmbH & Co. KG, Germany), was used to measure the GCV, following the ISO 1928:2020 standards (**Paper II**). The bomb calorimeter used for the pellets was also used for measuring the energy content of the wood and bark samples from the native tree species at 50% moisture (**Papers I** AND **III**). The net calorific value (NCV) for the pellets was calculated at two different moisture contents 5% and 10%, as described in SFS-EN ISO 18125:2017 (SFS 2017).

The Inductively Coupled Plasma - Optical Emission Spectrometry (ICP-OES) (**Papers I**, **II**, and **III**) was applied for describing the elemental content, including sulfur (S), of the samples. In **Paper I**, an accredited service laboratory determined the chlorine (Cl) content of the pellets in accordance with SFS-EN 15408:2011 (SFS 2011). The applied method was carried out by determining the dissolved anions by applying liquid chromatography of ions, based on the SFS-EN ISO 10304-1: 2007 (SFS 2007). Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) was used to detect the chlorine (Cl) content of wood and bark samples for **Paper III**. Before ICP-OES and ICP-MS, the samples were treated using a microwave-assisted acid digestion, EPA 3051 method, with a CEM Microwave Accelerated Reaction System, Model MARS 5 (CEM Corporation, Charlotte, NC, USA). The combustion analysis was conducted for measuring carbon (C) and nitrogen (N), using an elemental analyzer Vario MAX Cube (Elementar Analysensysteme GmbH) (**Paper III**). For **Paper I**, the contents of the monosaccharides, soluble and insoluble lignin, extractives, and ash were determined as instructed in Hayes (2012).

The ash content was measured according to SFS-EN 18122:2015, at 550 °C for **Paper II** and **Paper III** (SFS 2015a). The volatile matter (VM) content, described in **Paper II** and **Paper III**, was measured at 900 °C, according to SFS-EN 18123:2015 (SFS 2015b). For measuring both the ash and VM, a muffle furnace, Naber N7 (Nabertherm GmbH, Germany) was used. The fixed carbon (FC) content was calculated for the last two studies using Eq. (4). A Soxhlet extraction was used for purification of the hydrochar, with methanol as the solvent, followed by high-resolution Fourier-transform ion cyclotron resonance mass spectrometry (FT-ICR MS) to determine the polar, with electrospray ionization (ESI), and nonpolar, with atmospheric-pressure photoionization (APPI), sample constituents.

$$FC = 100 - (MC + A + VM) \tag{4}$$

where *FC*: Fixed Carbon (w-%)
MC: Moisture Content (w-%)
A: Ash (w-%)
VM: Volatile Matter (w-%)

The overall results from testing the pellets (**Paper I**) were compared to the suggested values of the SFS-EN ISO 17225-6:2014, quality class A, and ENplus Quality Certification Scheme for wood pellets, quality class B (ISO 2014; European Pellet Council 2015). The first refers to the highest requirements for pellets produced from herbaceous biomass, and the second to minimum thresholds for wood pellets. Due to the different structures of herbaceous and woody biomass, there are different certification schemes, with higher requirements for wood pellets. The SFS-EN 17225-6:2014, quality class B, was also used as a reference point for the elemental content of coffee silverskin and spent coffee samples in **Paper II**, as it can be used other biomass types as well (SFS 2014). The same pattern was followed by the elemental content of wood samples of the native tropical species, using SFS-ISO 17225-4:2021 quality class B2 (ISO 2021). The B2 class of this scheme refers to by-products and residues from the wood processing industry, with a moisture content between 15% and 55%. As the tested material was part of the stem, with wood being separated from bark, this scheme was more suitable for evaluating the elemental content of the species.

In **Paper I**, the study materials were obtained from a single experimental trial for each species, limiting the available biomass for pellet production. The harvested stalks were stored in industrial bags outdoors and in a shed for a year before pelletizing. Even though there was no contact with soil or exposure to sunlight or water, this long period could still affect the crop properties The silverskin materials, **Paper II**, were collected from three different locations, with some of them amounting to small quantities. This fact limited the feedstock availability, and the produced oils and hydrochars were obtained from two runs of the HTL process for each sample. The overall liquid and solid products from each sample were combined in single batches, one from each. Some of the wood and bark materials from the native tropical species, **Paper III**, which did not have adequate material for analysis, could not be restocked due to the long distance and the shipping cost. In addition, the samples represented three individual trees per species, and we included them in all tests to make a reliable comparison. In a very few cases of bark material, there was enough material from two trees, and in two cases from a single tree. The distribution data represent only the Cerrado biome, with potential bias, as no data were available for the Caatinga biome. An illustrative structure of the thesis is shown in **Fig. 5**, which summarizes the applied processes and methods.

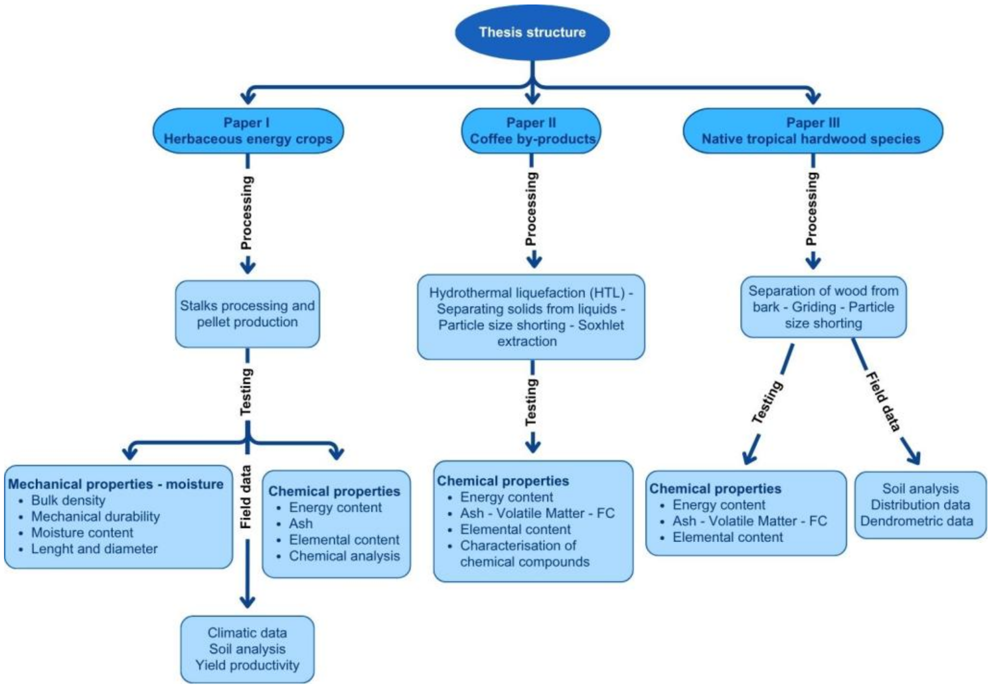

Figure 5. Structure of the thesis describing the type of material in each study, the applied processes, as well as the testing methods, and the additional collected data.

RESULTS

Pellet production from energy crops

The weather data obtained showed that the lowest temperature was -20 °C, whereas the highest was 21.9 °C. In addition, the annual precipitation observed ranged from 107.2 mm to 205 mm. The topsoil in the cultivation area was classified as medium-fine sand and humus, containing 6%–12% organic matter and having a pH of 6.3. The characterization of the yield productivity started for a period of 3 years for giant knotweed and 2 years for Virginia mallow. The dry matter yield (DMY) varied between 5.41 odt ha^{-1} yr^{-1}, not fertilized and only stems were harvested, and 27.67 odt ha^{-1} yr^{-1}, fertilized and both stems and leaves harvested, for giant knotweed. Virginia mallow had corresponding results of 6.46 odt ha^{-1} yr^{-1}, fertilized and only stems were harvested, and 16.72 odt ha^{-1} yr^{-1}, fertilized and both stems and leaves harvested (**Table 3**). The peak of yield was observed when harvesting occurred between July and September for both crops.

The bulk density of the produced pellets was between the recommended thresholds suggested by the certification schemes, being 677.71 $kg{\cdot}m^{-3}$ for giant knotweed and 725.18 $kg{\cdot}m^{-3}$ for Virginia mallow. The pellets from both species did not meet the minimum mechanical durability requirements. Giant knotweed pellets performed better results with 96.7%, being slightly lower than the recommended 97%, while the corresponding number of Virginia mallow was 92.9%. The moisture content decreased gradually from raw material to pellets, dropping by about 2-3 units at each processing stage. The moisture content of the pellets fluctuated between 5.9% and 6.69%, while the values below 10% aligned with both certification schemes. The observed diameter was approximately 8.1 mm for both species, whereas the giant knotweed pellets were longer, with a mean length of 29.14 mm, compared to Virginia mallow pellets, which were 21.99 mm.

The energy content of the pellets was close to 20 $MJ{\cdot}kg^{-1}$ at a moisture content of 5%, and between 17.2 $MJ{\cdot}kg^{-1}$ and 17.5 $MJ{\cdot}kg^{-1}$ at a moisture content of 10%. Giant knotweed pellets resulted in better ash content, by not exceeding the limit, compared to Virginia mallow, which had the corresponding value slightly higher than the ENplus limit. The content of chlorine (Cl) and sulfur (S), two elements with dense corrosive characteristics, was in accordance with the recommendations. Similarly, a group of other elements that need to be reported had met the suggested requirements. There was variation in the content of monosaccharides and soluble and insoluble lignin, with giant knotweed having higher values in some and Virginia mallow in others, but with no significant practical difference. On the other hand, the content of the extractives was almost double for Virginia mallow compared to that of giant knotweed. An overview of the pellet test results, compared with the certification schemes, is shown in **Table 4**.

Table 3. The yield productivity estimated yearly, including dry matter content (DMC) (w-%), fresh weight yield (FWY) (t·ha^{-1}), and dry matter yield (DMY) (t·ha^{-1}) of giant knotweed and Virginia mallow, as well as the harvested part from each crop. e: early harvest (April, May, June), l: late harvest (July, August, September), S: stems, L: leaves, *: not fertilized. Standard errors are presented in parentheses.

Species	Year	DMC	FWY	DMY	Parts of the crop
Giant knotweed	2012	20.8	70.2	14.64 (1.74)	S - L (l)
		27.2	88.72	24.15(2.83)	S - L (l)
		36.6	75.5	27.67 (3.40)	S - L (l)
		31.6	41.67	15.27	S (l)
	2013	87.3	8.83	7.71 (1.31)	S (e)
		64.3*	8.42*	5.41* (0.35)	S (e)
	2014	15.9	109.7	17.5	S - L (e)
		37.9	59.44	22.6	S - L (l)
Virginia mallow	2013	84	7.69	6.46 (0.81)	S (e)
	2014	81*	10.1*	8.2* (0.40)	S (e)
		37	45.2	16.72	S - L (l)

Table 4. Evaluation of physical and chemical characteristics of the pellets studied based on certification schemes ISO and ENplus.

Characteristics	Giant Knotweed - ISO/ENplus	Virginia mallow - ISO/ENplus
Moisture content	Pass/Pass	Pass/Pass
Net calorific value	Pass/Pass	Pass/Pass
Ash	Pass/Pass	Pass/Fail
Bulk density	Pass/Pass	Pass/Pass
Mechanical durability	Fail/Fail	Fail/Fail
Sulfur (S)	Pass/Pass	Pass/Pass
Chlorine (Cl)	Pass/Pass	Pass/Pass

Hydrothermal conversion of coffee by-products for bioenergy and biochemical applications

The HTL process of the assessed coffee by-products yielded hydrochar, a water-rich light oil, and a water-insoluble heavy oil. Spent coffee yielded higher amounts of hydrochar and heavy oil, whereas silverskin produced almost twice as much light oil as spent coffee. The energy content of the studied materials was significantly improved after the HTL process. The untreated materials released energy between 19 MJ·kg^{-1} and 22 MJ·kg^{-1}, which can be considered comparable to the tested Norway spruce sawdust, which was 19.16 MJ ·kg^{-1}. The hydrochar, on the other hand, reached up to 34.3 MJ·kg^{-1}, with spent coffee hydrochar recording the highest values, in **Fig. 6**. HTL improved combustion characteristics by lowering the ash in each case. Similarly, the volatile matter content decreased after hydrothermal conversion, in contrast to the increased fixed carbon content. Overall, spent coffee grounds depicted the most promising features for combustion applications (**Fig. 7**).

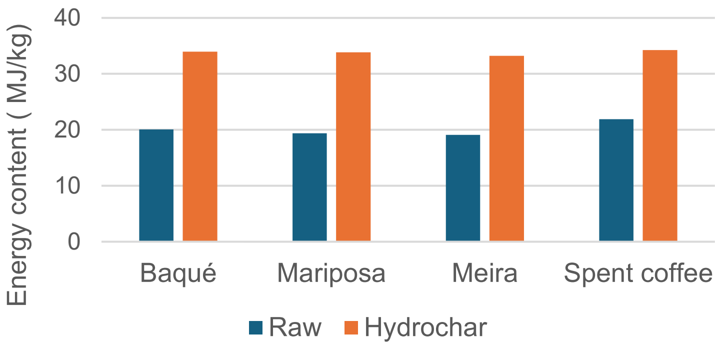

Figure 6. Energy content of the assessed coffee by-products before and after the hydrothermal treatment.

Most target chemical elements did not exceed the recommended thresholds, with copper (Cu) reporting notably higher levels than the limits, particularly in the silverskin hydrochar samples. Nickel (Ni) showed values above the limits for BA-HC, MA-HC, and SC-HC, with the latter being slightly above the limit. In addition, MA-HC was the only tested sample in which zinc (Zn) content did not align with the recommended limit value.

The chemical compounds detected in the silverskin samples showed no significant differences in composition, but there were differences in the quantities of certain compounds. The delivered light and heavy oil, both for silverskin and spent coffee HTL-treated materials, indicated noticeable amounts of fatty acids and alkaloids, as well as the presence of nonpolar compounds, such as triterpenoids and hydrocarbons.

Polar compounds, for instance, carbohydrate degradation products or types of alkaloids, were only contained in the light oils. The obtained oil fractions are described by high complexity, consisting of aliphatic and aromatic compounds. More specifically, there was considerable diversity of compounds mainly described as condensed aliphatic and aromatic hydrocarbons, unsaturated and hydroxy/epoxy fatty acids, triterpenoids, and alkaloids, among others, which were found based on the positive ion (+) APPI detection. The negative-ion (–) ESI included carbohydrates and their degradation products, aliphatic saturated and unsaturated amides, fatty acids (mainly C16 or C18 skeleton), and acidic oxyaromatic compounds (**Fig. 8**).

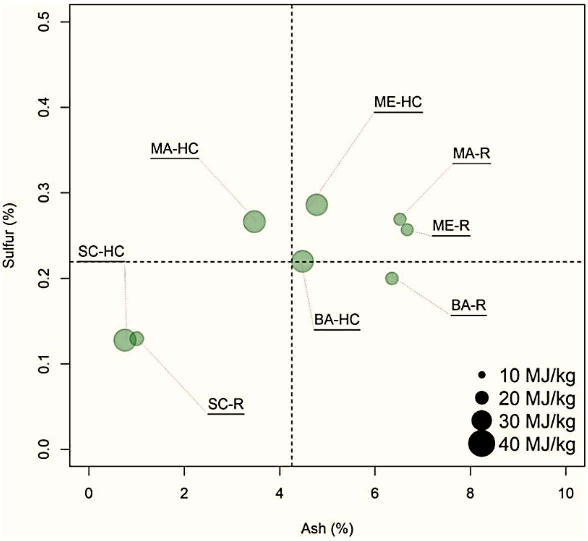

Figure 7. Content of ash (w-%), sulfur (S) (w-%), and energy (MJ ·kg−1) content from silverskin and spent coffee, both for raw and hydrothermal treated samples. The dashed lines refer to the mean ash, 4.25%, and sulfur, 0.22%.

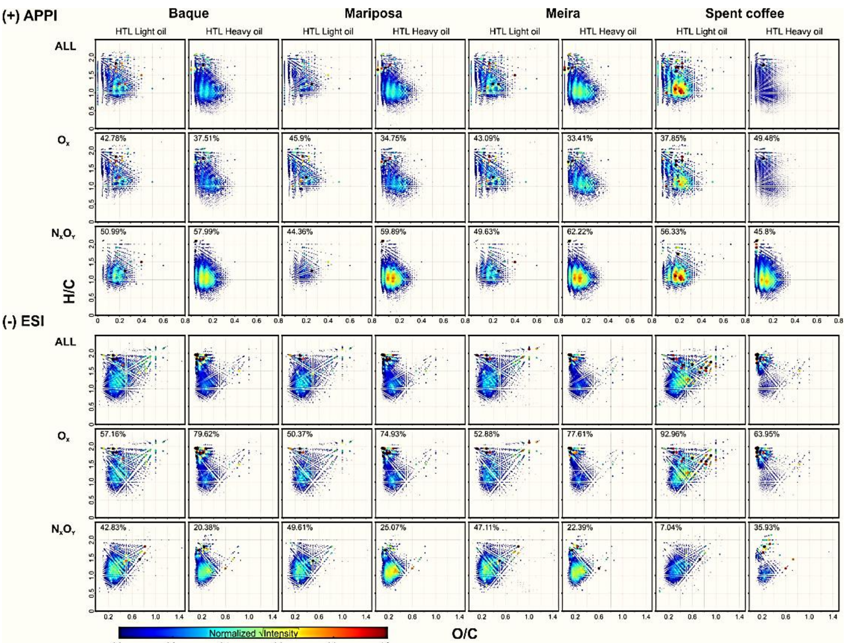

Figure 8. Van Krevelen diagrams for the CHO and CHNO compounds in the HTL light and heavy oils of coffee silverskin and spent coffee grounds, determined by Fourier-transform ion cyclotron resonance mass spectrometry, both with atmospheric-pressure photoionization (APPI), positive ion, and electrospray ionization (ESI), negative ion.

Native hardwood species from Brazil for energy applications

The assessed tree species exhibited a broad distribution, being spotted in 103 plots of the Brazil's NFI, and sampling in total 3734 tree measurements within the Cerrado biome (see **Fig. 9**). Four species numbered more than 400 trees each, with a peak of 550 trees. Some of those species were well represented in the area, whereas others were restricted to parts of the Cerrado, such as the northeast. The observed dendrometry features, such as the mean height and DBH, varied from 5 m to 11 m and from 0.07 m to 0.17 m, respectively, indicating the complexity of the forest structure. The soil from the sampling area was classified as strongly acidic loamy sand, with a mean pH of 5.1.

The measured energy content of the wood specimens, the average GCV was approximately 18.5 MJ·kg^{-1}, slightly higher than the corresponding mean value for the bark specimens. On the contrary, wood samples had less ash content, between 0.32% and 0.87%,

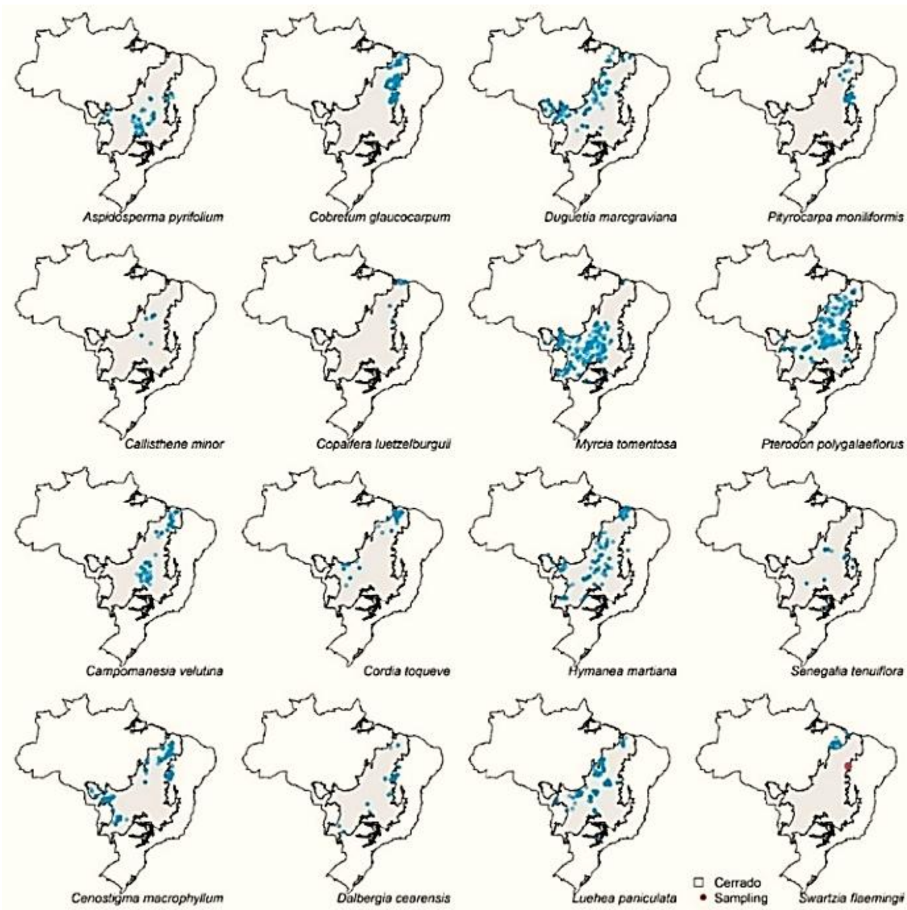

Figure 9. Distribution of the investigated species as recorded in the Cerrado biome based on the Brazilian National Forest Inventory.

compared to those from bark that ranged between 1% and 4.45%. Both sample types had similar carbon (C) content, averaging 50%. Based on the elemental analysis, almost all the wood samples were within the standard limits for the target elements. *D. marcgraviana* was the only species that had slightly higher content of sulfur than the certification limit. A summary ranking system was developed to identify the best-suited species for combustion applications. based on energy, ash, and chlorine (C) and sulfur (S) contents (**Fig. 10**). *P. polygalaeflorus* was the topmost among the species investigated, encompassing the highest rank, considering high energy, and low ash, chlorine (C), and sulfur (S) contents, followed by *L. paniculata*, and *A. pyrifolium*.

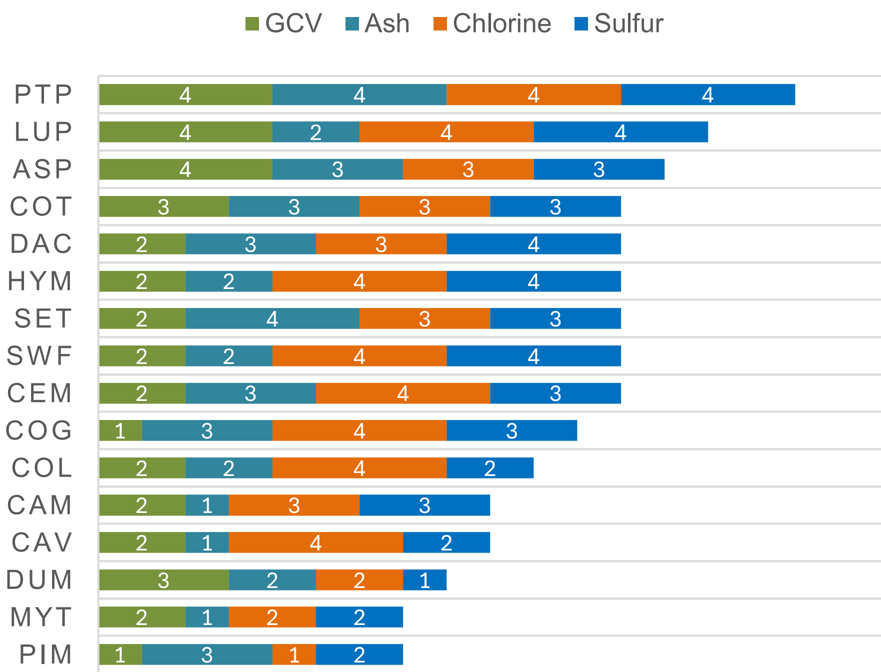

Figure 10. Synthetic ranking of the investigated species based on the variables gross calorific value (GCV), ash, chlorine, and sulfur content. For GCV, a higher value refers to a better rank, and for the rest of the variables, the lower the better, the higher the score.

DISCUSSION

The present thesis focused on different biomass sources to expand the potential feedstocks for producing energy and extracting chemical compounds. All the materials studied are newly introduced and lack sufficient research on energy production. The thesis argues that, despite the ongoing and increasing demand for energy production, there are plenty of resources that could be considered part of green economy development. Biomass utilization is a complex process that encompasses sustainable feedstock availability, transparency in supply chain systems, and products that meet high-quality standards. Even though there are similarities across all biomass resources, the distinguishing differences determine the processes required for effective application. In this regard, a well-organized plan is needed to clarify certain characteristics for better describing the best-suited applications.

Advancing herbaceous energy crops for pelletizing

The ongoing need to reduce dependence on conventional fuels has raised awareness of the importance of advancing biomass use. Densified solid biomass fuels like pellets outperform wood chips or firewood by saving space, containing less water, and releasing more energy. A greater reflection of bioenergy is the high-quality products and services it delivers. In **Paper I**, two newly introduced herbaceous crops were examined as potential feedstock for pellet production in Finland, demonstrating good potential. The crops assessed in **Paper I** belong to the group used to produce second-generation biofuels, thereby avoiding competition with food production. This factor is of great importance for improving public acceptance and eliminating conflicts that emerged when food crops were used to produce biofuels (Naik et al. 2010).

The resulting yields of giant knotweed and Virginia mallow are comparable to those reported in other studies for bioenergy production. *Polygonum sachalinensis* yielded 5.13 odt ha^{-1} yr^{-1}, not fertilized, and 9.58 odt ha^{-1} yr^{-1} for *Sida hermaprhodita*, fertilized, in Lithuania (Slepetys et al. 2012). In Poland, Virginia mallow resulted yields between 7.47 odt ha^{-1} yr^{-1} to 9.19 odt ha^{-1} yr^{-1} in a 4-year period and varied from 6.5 odt ha^{-1} yr^{-1} to 9.6 odt ha^{-1} yr^{-1} (Borkowska et al. 2009; Oleszek et al. 2020). Between the lowest unfertilized productivity values, harvesting only stems, of the two crops, giant knotweed reported 5.41 odt ha^{-1} yr^{-1} whereas Virginia mallow 8.2 odt ha^{-1} yr^{-1}. Energy crops could be associated with ecological aspects, such as soil restoration and improved productivity in marginal and degraded lands (Nijsen et al. 2012; Nackley et al. 2013). For instance, marginal lands in rural regions with low food crop productivity can be considered for energy production (Csikós and Tóth 2023). Abandoned lands, where agricultural activities previously occurred and are currently not considered for yielding high productivity, have the capacity to cultivate dedicated energy crops (Field et al. 2008; Canadell and Schulze 2014). Environmental assessments could help develop comprehensive crop profiles to support better decision-making on species choice and management applications (González-García et al. 2012; González-García et al. 2014).

The physical and chemical characteristics of pellets are associated with storing, transportation, and the applications of use. Giant knotweed and Virginia mallow pellets achieved bulk density within the reference standards. In other case studies, giant knotweed pellets had a bulk density of 509.9 $kg \cdot m^{-3}$, whereas Virginia mallow pellets had 570 $kg \cdot m^{-3}$ and 999.3 $kg \cdot m^{-3}$ (Jasinskas et al. 2014; Ţîţei and Andreoiu 2017; Streikus et al. 2017). Even though both crops had lower mechanical durability compared to the certification schemes, there is room for improvement in mechanical durability, either as pretreatment or during pelletizing. Heating biomass before pelletizing improves lignin binding behavior (Uslu et al. 2008). Higher moisture content increases binding and activates water-soluble compounds, thereby enhancing that effect (Lindley and Vossoughi 1989; Kaliyan and Vance Morey 2009).

The energy content of the studied pellets is comparable to values from other species, both wood and herbaceous. Pellets from commercial wood species had NCV ranging from 14.41 $MJ \cdot kg^{-1}$ to 17.91 $MJ \cdot kg^{-1}$, with an average moisture content of 10.1% (Telmo and Lousada 2011). The gross calorific value of giant knotweed and Miscanthus pellets was about 19 $MJ \cdot kg^{-1}$ (Streikus et al. 2017). Both species produced pellets within the ISO standards for ash content, but only giant knotweed met the ENplus standards, with Virginia mallow slightly above the limit. Further trials over longer periods could help better determine the ash content. For instance, winter harvesting could help reduce ash content (Burvall 1997; Christian et al. 2006).

Developing different mixtures of biomass materials could improve pellet characteristics, enabling the use of more materials for fuel production (Hernández-Neri et al. 2022). It should be noted that many factors determine how well performance a fuel could have. Factors such as the harvesting season and storing period of the biomass, solid fuels geometry, type and condition of the boiler, and even the feeding process of the fuel could play a role in combustion properties and released emissions (Lehtikangas 2001; Prade et al. 2012; Nižetić et al. 2019; Kraszkiewicz et al. 2022; Petlickaitė et al. 2023; Lio et al. 2025). Thus, it can be concluded that the development of biomass fuels should occur in parallel with other needed sectors for successful implementations.

Broad knowledge is essential to a better understanding of the practices needed to support environmental benefits through the cultivation of bioenergy feedstocks (Lemus and Lal 2005). Priority should be given to enhancing biodiversity and carbon sequestration when deciding which degraded land will be planted with energy crops (Tudge et al. 2025). Thus, biomass feedstocks derived from sustainable production could contribute to social benefits, for example, the development of rural areas, restore soil with depleted nutrients, and improve biodiversity habitats (Paine et al. 1996; Mehmood et al. 2017; La Torre Ugarte 2026).

Certification schemes were developed to verify every step of biofuels production, ensuring the supply of high-quality products to consumers. Setting standards as part of certification schemes strongly provides the necessary tools for validating fuel characteristics alongside the related production and trade processes (Lewandowski and Faaij, 2006). Both giant knotweed and Virginia mallow **(Paper I**) showed rather good results, meeting most of the thresholds recommended by certification schemes. That sets the stage for further investigation to address the very few drawbacks observed. New studies could examine other variables to increase the potential applications of these two crops. For example, Giant reed (*Arundo donax* L.) is a tall, perennial, rhizomatous grass that can be used for energy, paper pulp, roofing thatch, and training stakes for orchards and vegetable crops (Lewandowski et al. 2003).

Waste side-streams for valuable products and services

The constant increase in organic solid waste led societies to develop sustainable and effective methods for disposal. Apart from conventional methods such as incineration and landfill disposal, rapid technological advancements enable the use of these feedstocks as energy and chemical sources. Thus, constant research will expand the recovery of value-added products and issue tailored solutions.

In **Paper II**, the hydrothermal conversion of coffee roasting by-products, silverskin and spent coffee grounds, yielded promising results, including rich in energy hydrochar and light and heavy oils as chemical resources. In recent years, HTL processing is gaining a growing attention for bio-oil production through valorization of food wastes and agricultural residues (Hu et al. 2017; Posmanik et al. 2017; Rao et al. 2018; Chen et al. 2020; Cutz et al. 2025). Previous studies have portrayed the potential of using silverskin as a source of chemical compounds, such as phenolics and fibers (Pourfarzad et al. 2013; Kulkarni et al. 2024; Boninsegna et al. 2025).

The hydrothermal treatment of silverskin yielded more liquids than spent coffee grounds, with the latter producing a higher volume of hydrochar. The energy content was upscaled, with the hydrochars having a mean value of about 33.8 $MJ \cdot kg^{-1}$, approximately 40% higher than that of the raw samples. Biochar from pyrolyzed silverskin reached up to 24.2 $MJ \cdot kg^{-1}$, while processed spent coffee grounds through torrefaction had energy content up to 27.28 $MJ \cdot kg^{-1}$ (Chen and Jhou 2020; Pozo et al. 2021). HTL biochar from corn stover had measured gross energy between 21 $MJ \cdot kg^{-1}$ and 25 $MJ \cdot kg^{-1}$, with higher values observed with treatment at 300 °C (Nava-Bravo et al. 2025). Based on that, HTL could produce energy-rich solid products compared to other conversion treatments, but the choice of feedstock and process settings plays a role in that as well.

The lowest ash content was found in the spent coffee hydrochar at 0.8%, slightly lower than in the raw material at 1.0%. The hydrothermal conversion reduced ash content in all tested samples, with Mariposa hydrochar dropping by 2.8 units. The ash content remained higher than that of solid biomass fuels, and treatments to reduce it are needed. Deashing of HTL-treated bark significantly reduced the ash content from 2.27%, before deashing, to 0.44% (Feng et al. 2014). The HTL treatment increased the content of the elements, with most showing a low increase and not exceeding the recommended threshold. Copper content was rather high in both hydrochars and raw materials, with the lowest levels in spent coffee hydrochar. Nickel and zinc observations were also elevated above the limits, with Baqué and spent coffee hydrochars including only nickel, while Mariposa hydrochar encompassing both nickel and zinc. The leaching approach might help reduce the levels of those elevated elements. For instance, leaching with ethylenediaminetetraacetic acid removed copper from wood waste (Nami Kartal, 2003).

All HTL liquids showed richness in their constituent profiles. Despite the different origins of the silverskin samples, strong similarities were noted in the chemical compositions. That contrasts with previous studies, which showed differences based on geographical origin and coffee varieties (Tan et al. 2016; Bessada et al. 2018a; Kresna et al. 2024). The HTL liquids from all samples contained different fatty acids and alkaloids, with caffeine being the main type of alkaloids. In addition, nonpolar compounds, like triterpenoids and hydrocarbons, were detected in both light and heavy oils. Polar, water-soluble compounds, on the other hand, were detected in light oils only, including carbohydrate degradation products or a few alkaloids, such as caffeine. These findings suggest that the hydrothermal valorization of coffee by-products could have potential for producing wood preservatives, cosmetics, and pharmaceutics (Barbero-López et al. 2018; Bessada et al. 2018b; Kamgang Nzekoue et al. 2022). Recently published studies illustrated additional possible applications arising from valorizing coffee by-products and scaling up the potential value-added products (Lee et al. 2023; Tsigkou et al. 2025). Substrate for biobutanol and hydrogen production, organic fertilizers, and soil amendment by removing heavy metals being some examples (Hijosa-Valsero et al. 2018; Mirzoyan et al. 2022; Jiang et al. 2023; Młynarczykowska and Orlof-Naturalna 2024).

HTL biomass processing requires further leveraging through optimized procedures and refinement to current challenges, achieve desired qualitative and quantitative outcomes, and enhance commercial prospects (Ross et al. 2010; Jena et al. 2011; Tekin et al. 2014; Pham et al. 2025; Tiwari and Mallick 2025). Technological improvements could positively impact logistics efficiency, with lower costs, and aggregate sustainable networks based on renewable resources (Gerssen-Gondelach et al. 2014; Chaudhary et al. 2025).

Sustainability pathways for retaining biodiversity

A strategy plan for utilizing biomass resources should include information on fuel characteristics and stock availability (Kataki and Konwer 2001; Ngugi et al. 2018). Furthermore, the production of biomass for producing solid biofuels should avoid the risk of biodiversity disturbance and, if possible, enhance biodiversity (Cramer Commission 2006). In **Paper III**, native tropical hardwood species from northern Brazil were examined to assess species availability, dendrometry traits, and combustion properties. Features, such as tree distribution, heights and DBH, and chemical characteristics, were presented aiming to suggest the most qualified species for energy production. The species *Cenostigma macrophyllum*, *Duguetia marcgraviana*, *Hymenaea martiana*, *Luehea paniculata*, *Myrcia tomentosa*, and *Pterodon polygalaeflorus* showed a broad distribution. These six species were detected in at least 8 plots and had individual measurements from 242 to 550. Regarding the height measurements, *Duguetia marcgraviana* and *Swartzia flaemingii* recorded the highest average heights, 10.87 m and 11.44 m, respectively, with the first species showing the highest height variability. *H. martiana* and *P. polygalaeflorus* depicted DBH from a few centimeters <10 cm to up 60 cm and the highest diameter variability. Providing knowledge of versatile tree characteristics better supports decision-making for forest management, disturbance monitoring, and integrating commercialization and biodiversity values (Marques 2006; Cotrina Sánchez et al. 2020; Silva Santos et al. 2026). Thus, robust focus has been given to developing new methods for more accurate and quicker data acquisition, such as terrestrial laser scanning and mobile laser scanning (Holvoet et al. 2025).

In the context of using the studied species for energy generation, the bark samples had GCV ranging from 18 $MJ \cdot kg^{-1}$ to 23 $MJ \cdot kg^{-1}$, while the corresponding values for the wood were 19.5 and 20 $MJ \cdot kg^{-1}$. The characterized energy contents are similar to those of other species, such as beech, being approximately 19.5 $MJ \cdot kg^{-1}$ (Vusić et al., 2021). Two case studies of native species from Sub-Saharan Africa revealed that five species averaged an energy content of 14.9 $MJ \cdot kg$-^{1}, and only two of 12 species exceeded 18 $MJ \cdot kg^{-1}$ (Lubwama et al. 2023; Manyatsha et al. 2025). Native species from Nigeria, particularly used as fuelwood, depicted an average GCV of 15.52 $MJ \cdot kg^{-1}$ (Yunusa et al. 2024). Examining other species from the Cerrado biome, the GCV was from 18.71 $MJ \cdot kg^{-1}$ to 19.5 $MJ \cdot kg^{-1}$ (Marques et al. 2020).

The ash content of all species remained below 1%, with *Aspidosperma pyrifolium Cenostigma macrophyllum*, *Pterodon polygalaeflorus* and *Senegalia tenuifolia* having ash contents even lower than 0.4%. It is estimated that about 480 million tons of ash are produced annually from the combustion of biomass, with need for proper removal and management (Munawar et al. 2021). These findings are in line with other species from Brazil, with ash ranging from 0.26% to 0.62% (Marques et al. 2020). The elemental analysis showed that only *Duguetia marcgraviana* had slightly higher sulfur levels than the ISO thresholds. The low corrosive profile of biomass fuels is attributed to the low maintenance cost of boilers (Paz et al. 2021). The aluminum content in *Callisthene minor* was significantly higher than in the other species. Cerrado soil is exceptionally saturated with Al, and some Vochysiaceae species, such as *Callisthene minor*, remove Al from the soil through the root system (Chenery 1948; Haridasan 1982; Furley and Ratter 1988; Andrade et al. 2011).

Shifting land cover, for instance, by extensively establishing pastures and food crop plantations, could negatively affect regional climatic conditions by unsettling the water cycle, which could subsequently impact the remaining native species (Sampaio et al. 2007). Croplands tend to have higher surface albedo, especially compared to lands covered by native species, leading to reduced precipitation and evapotranspiration (Costa et al. 2007). Modeling scenarios give provision that deforestation in the Cerrado could lengthen the dry season, thereby aggravating conditions for native vegetation (Costa and Pires 2010). Shifting land cover in conjunction with climatic changes could further stress both flora and fauna in Cerrado (Hofmann et al. 2025). Longer dry seasons and the expansion of crop plantations could make biomes even more prone to wildfires (Jolly et al. 2015; Schmidt and Eloy 2020). Raising public awareness of sustainable management practices and providing necessary information on the bioenergy potential of native species could reduce illegal activities (Gama et al. 2022). A better understanding of the capacity of native species for commercialization might act as an incentive for improving current policies, which in turn might lead to having more protected areas. For example, only 7% of the Cerrado biome is covered by legislative protection, while the corresponding number of protected areas in the Amazon forest is 46% (Soares-Filho et al. 2014).

Apart from energy production, the species studied are described by ecological and medicinal services as well. *Myrcia tomentosa* is described as a pioneer species (Imatomi et al. 2013). *Aspidosperma pyrifolium*, *Cenostigma macrophyllum*, and *Piptadenia moniliformis* are linked to honey production in Piauí (Aleixo et al, 2015). In addition, these four species, along with *C. glaucocarpum*, show suitability for ecological restoration (Conceição Sabino et al. 2021; Lima et al. 2021; Ribeiro et al. 2021, Vourlitis et al. 2026). Savanna tree species have thicker bark compared to forest trees, giving them the ability to better tolerate fire damage (Hoffman et al. 2012). *L. paniculata* has shown potential for cosmetic and antioxidant applications, *P. polygalaeflorus* has demonstrated anti-inflammatory effects, *Hymenaea* species, particularly *H. martiana*, are widely used in Northeast Brazil to treat inflammation and rheumatism (Albuquerque et al. 2007; Velozo et al. 2013; Boniface et al. 2017; Leal et al. 2018; Nunes et al. 2018).

Future roadmaps and conclusions

Biomass offers resilience, with high availability in various forms, and new methods are being developed for novel conversions. Biomass resources do not compete with one another; on the contrary, they complement one another and are characterized by solidarity and the provision of tailored solutions. In addition, this feature promotes adaptability by integrating a range of biomass feedstocks across different processing methods. Nowadays, securing domestic energy autarky is a high priority, and increasing biomass utilization is more crucial than ever. A genuine way to achieve this is to obtain multiple benefits from available resources that could originate at the local level. Improving pellet properties could be achieved with blend adjustments. Introducing alternative feedstocks will increase the overall production capacity. Technological advancements help better valorize materials, such as biomass by-products, that were previously difficult to process. Biomass-driven production systems may enhance the economic viability of native species conservation and support the livelihoods of indigenous communities. These aspects could enhance commercial applications, as novel and promising products and services could accrue. Certification schemes pave the way for the sustainable utilization of emerging resources.

Summarizing the findings of all the papers from this thesis, the assessed biomass feedstocks showed potential for integration into energy systems. In **Paper I**, energy crops depicted an exceptionally good profile for pellet production in Nordic conditions, especially when compared to other herbaceous crops. Coffee waste products in **Paper II** could be scaled up through hydrothermal conversion, both in terms of energy and chemical compound production. Native tropical species from Northeastern Brazil, as demonstrated in **Paper III**, provide evidence for altering current uses by integrating them into sustainable bioenergy systems, while preserving ecologically driven traits. Nevertheless, further investigation will be needed to clarify the necessary practices and optimized methods for successful incorporation into commercial supply chains.

REFERENCES

AGEB (March 30, 2023), Contribution of biomass energy to the German energy mix from 2005 to 2022. In Statista [Graph]. https://www.statista.com/statistics/737705/energy-mix-biomass-germany/. Accessed 10 July 2024.

Aguiar LMS, Machado RB, Françoso RD, Neves AC, Fernandes GW, Pedroni F, Lacerda MS, Ferreira GB, Araujo Silva JD, Bustamante M, Diniz S (2015) Cerrado: terra incógnita do século 21. Ciência Hoje 330: 32-37. https://mosaicosvp.com.br/2017/03/09/cerrado-terra-incognita-do-seculo-xxi/. [in Portuguese].

Albuquerque UP de, Muniz de Medeiros P, Almeida ALS de, Monteiro JM, Machado de Freitas Lins Neto E, Gomes de Melo J, Santos JP dos (2007) Medicinal plants of the Caatinga (semi-arid) vegetation of NE Brazil: A quantitative approach. J. Ethnopharmacol. 114(3): 325-354. https://doi.org/10.1016/j.jep.2007.08.017.

Aleixo D de L, Araújo WL de, Agra R da S, Maracajá PB, Sousa MJ de O (2015) Mapeamento da flora apícola arbórea das regiões pólos do estado do Piauí. Revista Verde de Agroecologia e Desenvolvimento Sustentável [S. l.] 9(4):262-270. https://www.gvaa.com.br/revista/index.php/RVADS/article/view/3447. [in Portuguese].

Anastasakis K, Biller P, Madsen RB, Glasius M, Johannsen I (2018) Continuous hydrothermal liquefaction of biomass in a novel pilot plant with heat recovery and hydraulic oscillation. Energies 11(10), article id 2695. https://doi.org/10.3390/en11102695.

Andrade-Lima D (1982) Present-day forest refuges in northeastern Brazil. Pages 245-251 in G. T. Prance, editor. Biological diversification in the tropics. Columbia University Press, New York.

Andrade LRM de, Gomes Barros LM, Echevarria GF, Velho do Amaral LI, Cotta MG, Rossatto DR, Haridasan M, Franco AC (2011) Al-hyperaccumulator Vochysiaceae from the Brazilian Cerrado store aluminum in their chloroplasts without apparent damage. Environ. Exp. Bot. 70(1): 37-42. https://doi.org/10.1016/j.envexpbot.2010.05.013.

Balcioglu G, Jeswani HK, Azapagic A (2023) Energy from forest residues in Turkey: An environmental and economic life cycle assessment of different technologies. Sci. Total Environ. Volume 874, article id 162316. https://doi.org/10.1016/j.scitotenv.2023.162316.

Ballesteros LF, Teixeira JA, Mussatto SI (2014) Chemical, functional, and structural properties of spent coffee grounds and coffee silverskin. Food Bioprocess Technol. 7: 3493-3503. https://doi.org/10.1007/s11947-014-1349-z.

Barbero-López A, López-Gómez YM, Carrasco J, Jokinen N, Lappalainen R, Akkanen J, Mola-Yudego B, Haapala A (2024) Characterization and antifungal properties against wood decaying fungi of hydrothermal liquefaction liquids from spent mushroom substrate and tomato residues. Biomass Bioenergy Volume 181, article id 107035. https://doi.org/10.1016/j.biombioe.2023.107035.

Barbero-López A, Ochoa-Retamero A, López-Gómez Y, Vilppo T, Venäläinen M, Lavola A, Julkunen-Tiitto R, Haapala A (2018) Activity of spent coffee ground cinnamates against wood-decaying fungi in vitro. BioResources 13:6555-6564. https://doi.org/10.15376/biores.13.3.6555-6564.

Berndes G, Hoogwijk M, Van den Broek R (2003) The contribution of biomass in the future global energy supply: a review of 17 studies. Biomass Bioenergy 25(1): 1-28. https://doi.org/10.1016/S0961-9534(02)00185-X.

Bessada SMF, Alves RC, Costa ASG, Nunes AM, Oliveira MBPP (2018a) *Coffea canephora* silverskin from different geographical origins: A comparative study. Sci. Total Environ. Volume 645: 1021-1028. https://doi.org/10.1016/j.scitotenv.2018.07.201.

Bessada SMF, Alves RC, Oliveira MBPP (2018b) Coffee silverskin: a review on potential cosmetic applications. Cosmetics 5(1):5. https://doi.org/10.3390/cosmetics5010005.

Beuchle R, Grecchi RC, Shimabukuro YE, Seliger R, Eva HD, Sano E, Achard F (2015) Land cover changes in the Brazilian Cerrado and Caatinga biomes from 1990 to 2010 based on a systematic remote sensing sampling approach. Appl. Geogr. Volume 58: 116-127. https://doi.org/10.1016/j.apgeog.2015.01.017.

Bhatia SK, Jagtap SS, Bedekar AA, Bhatia RK, Patel AK, Pant D, Rajesh Banu J, Rao CV, Kim YG, Yang YH (2020) Recent developments in pretreatment technologies on lignocellulosic biomass: Effect of key parameters, technological improvements, and challenges. Bioresour. Technol. Volume 300, article id 122724. https://doi.org/10.1016/j.biortech.2019.122724.

Bichel A, Telles TS (2021) Spatial dynamics of firewood and charcoal production in Brazil. J. Clean. Prod. Volume 313, article id 127714. https://doi.org/10.1016/j.jclepro.2021.127714.

Bickerton HJ (2011) Recovery strategy for the Virginia Mallow (Sida hermaphrodita) in Ontario. Ontario Recovery Strategy Series. Prepared for the Ontario Ministry of Natural Resources, Peterborough, Ontario, 16 pp. https://www.registrelep-sararegistry.gc.ca/virtual_sara/files/plans/rs_virginia_mallow_e_final.pdf. Accessed 8 April 2021.

Bioenergy Europe (2025) Bioenergy Landscape - Statistical Report Pocket edition. Place du Champ de Mars 2, 1050 Brussels, Belgium, 52 pp. https://bioenergyeurope.org/wp-content/uploads/2026/02/Booklet-Single-Page-Website.pdf. Accessed 10 January 2026.

Bomfim ASCd, de Oliveira DM, Walling E, Babin A, Hersant G, Vaneeckhaute C, Dumont M-J, Rodrigue D (2023) Spent coffee grounds characterization and reuse in composting and soil amendment. Waste 1(1): 2-20. https://doi.org/10.3390/waste1010002.

Boniface PK, Ferreira SB, Roland Kaiser C (2017) Current state of knowledge on the traditional uses, phytochemistry, and pharmacology of the genus *Hymenaea*. J. Ethnopharmacol. 206: 193-223. https://doi.org/10.1016/j.jep.2017.05.024.

Boninsegna MA, Piscopo A, De Bruno A, Taglieri T, Chinè V, Poiana M (2025) Sustainable recovery of bioactive compounds from coffee silverskin. Sustain. Food Technol. 4(1): 1032-1044. https://doi.org/10.1039/d5fb00485c.

Borkowska H, Molas R, Kupczyk A (2009) Virginia fanpetals (*Sida hermaphrodita* Rusby) cultivated on light soil; height of yield and biomass productivity. Pol. J. Environ. Stud. 18(4): 563-568.

Bose D, Bhattacharya R, Rizvi A, Poonia A, Saraf D, Ghodke P (2022) Biorefineries: An Integrated Approach for Sustainable Energy Production. In: Verma, P. (eds) Thermochemical and Catalytic Conversion Technologies for Future Biorefineries. Clean Energy Prod. Technol. Springer, Singapore. https://doi.org/10.1007/978-981-19-4316-4_8.

Bostedt G, Mustonen M, Gong P. (2015) Increasing forest biomass supply in northern Europe – countrywide estimates and economic perspectives. Scand. J. For. Res. 31(3): 314-322. https://doi.org/10.1080/02827581.2015.1089930.

Brazilian Tree Industry (IBÁ) (2025). IBÁ Annual Report 2025. https://iba.org/wp-content/uploads/2025/10/iba-annualreport-2025.pdf. Accessed 15 January 2026.

Burvall J (1997) Influence of harvest time and soil type on fuel quality in reed canary grass (*Phalaris arundinacea* L.). Biomass Bioenergy 12(3): 149-154. https://doi.org/10.1016/S0961-9534(96)00064-5.

Cahyanti MN, Doddapaneni TRKC, Kikas T (2020) Biomass torrefaction: An overview on process parameters, economic and environmental aspects and recent advancements. Biores. Technol. Volume 301, article id 122737. https://doi.org/10.1016/j.biortech.2020.122737.

Campos-Vega R, Loarca-Piña G, Vergara-Castañeda HA, Oomah BD (2015) Spent coffee grounds: A review on current research and future prospects. Trends Food Sci. Technol. Volume 45, Issue 1: 24-36. https://doi.org/10.1016/j.tifs.2015.04.012.

Canadell, J, Schulze E (2014) Global potential of biospheric carbon management for climate mitigation. Nat. Commun. 5, article id 5282. https://doi.org/10.1038/ncomms6282.

Castello D, Pedersen TH, Rosendahl LA (2018) Continuous hydrothermal liquefaction of biomass: A critical review. Energies 11(11), article id 3165. https://doi.org/10.3390/en11113165.

Cervera-Mata A, Delgado G, Fernández-Arteaga A, Fornasier F, Mondini C (2022) Spent coffee grounds by-products and their influence on soil C–N dynamics. J. Environ. Manag. Volume 302, Part B, article id 114075. https://doi.org/10.1016/j.jenvman.2021.114075.

Chaudhary A, Rathour RK, Solanki P, Mehta Kakkar P, Pathania S, Walia A, Baadhe RR, Bhatia RK (2025) Recent technological advancements in biomass conversion to biofuels and bioenergy for circular economy roadmap. Renewable Energy Volume 244, article id 122714. https://doi.org/10.1016/j.renene.2025.122714.

Chen WH, Lin YY, Liu HC, Baroutian S (2020) Optimization of food waste hydrothermal liquefaction by a two-step process in association with a double analysis. Energy Volume 199, article id 117438. https://doi.org/10.1016/j.energy.2020.117438.

Chen YC, Jhou SY (2020) Integrating spent coffee grounds and silver skin as biofuels using torrefaction. Renewable Energy Volume 148: 275-283. https://doi.org/10.1016/j.renene.2019.12.005.

Chenery EM (1948) Further notes on aluminium in trees. Emp. For. Rev. 27(1): 129–130. http://www.jstor.org/stable/42599707.

Cherubini F, Bird ND, Cowie A, Jungmeier G, Schlamadinger B, Woess-Gallasch S (2009) Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. Resour. Conserv. Recycl. 53(8): 434-447. https://doi.org/10.1016/j.resconrec.2009.03.013.

Christian DG, Yates NE, Riche AB (2006) The effect of harvest date on the yield and mineral content of *Phalaris arundinacea* L. (reed canary grass) genotypes screened for their potential as energy crops in southern England. J. Sci. Food Agric. 86: 1181-1188. https://doi.org/10.1002/jsfa.2437.

Chrysargyris A, Antoniou O, Xylia P, Petropoulos S, Tzortzakis N. (2021) The use of spent coffee grounds in growing media for the production of *Brassica* seedlings in nurseries. Environ. Sci. Pollut. Res. 28: 24279-24290. https://doi.org/10.1007/s11356-020-07944-9.

Coelho Junior LM, Burgos MC, Santos Júnior EP, Pinto PALDA (2019) Regional concentration of the gross value of production of firewood in Paraíba. FLORAM 26(3), article id e20170887. https://doi.org/10.1590/2179-8087.088717.

Conceição Sabino F da, Bastos de Souza LS, Gonçalves de Souza MA, Alves de Barros JP, Rodrigues de Lucena LR, Maniçoba da Rosa Ferraz Jardim A, Penna Rocha AK, Freire da Silva TG (2021) Morphological characteristics, biomass accumulation and gas exchange of an important species native for restoration in Semi-arid Brazilian areas affected by salt and water stress. Plant Stress 2, article id 100021. https://doi.org/10.1016/j.stress.2021.100021.

Cotrina Sánchez DA, Barboza Castillo E, Rojas Briceño NB, Oliva M, Torres Guzman C, Amasifuen Guerra CA, Bandopadhyay S (2020) distribution models of timber species for forest conservation and restoration in the Andean-Amazonian landscape, North of Peru. Sustainability 12(19):7945. https://doi.org/10.3390/su12197945.

Costa MH, Yanagi SNM, Souza PJOP, Ribeiro A, Rocha EJP (2007) Climate change in Amazonia caused by soybean cropland expansion, as compared to caused by pastureland expansion. Geophys. Res. Lett. 34, article id L07706. https://doi.org/10.1029/2007GL029271.

Costa MH, Pires GF (2010) Effects of Amazon and Central Brazil deforestation scenarios on the duration of the dry season in the arc of deforestation. Int. J. Climatol. 30: 1970-1979. https://doi.org/10.1002/joc.2048.

Cramer Commission (2006) Testing framework for sustainable biomass. Low Carbon Vehicles Partnership (LowCVP), London.

Cross S, Welfle AJ, Thornley P, Syri S, Mikaelsson M (2021) Bioenergy development in the UK & Nordic countries: A comparison of effectiveness of support policies for sustainable development of the bioenergy sector. Biomass Bioenergy Volume 144, article id 105887. https://doi.org/10.1016/j.biombioe.2020.105887.

Csikós N, Tóth G (2023) Concepts of agricultural marginal lands and their utilisation: A review. Agricultural Systems Volume 204, article id 103560. https://doi.org/10.1016/j.agsy.2022.103560.

Cutz L, Misar S, Font B, Al-Naji M, de Jong W (2025) Hydrothermal liquefaction of Spanish crude olive pomace for biofuel and biochar production. J. Anal. Appl. Pyrolysis Volume 188, article id 107050. https://doi.org/10.1016/j.jaap.2025.107050.

Dimitriou I, Rosenqvist H, Berndes G (2011) Slow expansion and low yields of willow short rotation coppice in Sweden; implications for future strategies. Biomass Bioenergy 35(11): 4613-4618. https://doi.org/10.1016/j.biombioe.2011.09.006.

Dussan K, Monaghan RFD (2018) Integrated thermal conversion and anaerobic digestion for sludge management in wastewater treatment plants. Waste Biomass Valor. 9, 65-85. https://doi.org/10.1007/s12649-016-9812-x.

El-Sayed IM, Salama WH, Badr MA (2024) Nitrogen and spent coffee ground for enhancing nutritional, morphological, flowering and antioxidant properties of *Chrysanthemum* (*Chrysanthemum morfolium* Ramat). Plant Physiol. Biochem. Volume 207, article id 108406. https://doi.org/10.1016/j.plaphy.2024.108406.

Ember. (June 1, 2023). Electricity generation in Finland in 2022, by source (in terawatt-hours). In *Statista* [Graph]. https://www.statista.com/statistics/1391223/finland-electricity-production-by-source/. Accessed 10 July 2024.

ENplus® (2025) ENplus® Statistics. Retrieved from https://enplus-pellets.eu/wp-content/uploads/2025/06/ENplus_Stats_2025-May.pdf.

Ericsson K, Nilsson LJ (2006) Assessment of the potential biomass supply in Europe using a resource-focused approach. Biomass Bioenergy 30(1): 1-15. https://doi.org/10.1016/j.biombioe.2005.09.001.

EurObserv'ER. (2024a). Primary energy production and gross inland consumption of solid biomass in Sweden from 2016 and 2022 (in million metric tons of oil equivalent). In Statista [Graph]. https://www.statista.com/statistics/799426/solid-biomass-production-consumption-sweden/. Accessed 3 January 2024.

EurObserv'ER. (2024b). Primary energy production from biogas in Greece from 2018 to 2022, by type (in ktoe*). In Statista [Graph].

https://www.statista.com/statistics/1455259/annual-biogas-primary-energy-production-by-type-greece/. Accessed 29 February 2024.

European Committee for Standardization Solid Biofuels (2009) Determination of moisture content. Oven dry method. Total moisture. EN 14774-1:2009, Brussels, Belgium.

European Pellet Council (EPC) (2013) Handbook for the certification of wood pellets for heating purposes. Version 2.0, Brussels, Belgium.

European Pellet Council (EPC) (2015) ENplus Handbook. Version 3.0, Brussels, Belgium.

Fan Q, Fu P, Song C, Fan Y (2023) Valorization of waste biomass through hydrothermal liquefaction: A review with focus on linking hydrothermal factors to products characteristics. Ind. Crops Prod. Volume 191, Part B, article id 116017. https://doi.org/10.1016/j.indcrop.2022.116017.

Feng S, Yuan Z, Leitch M, Xu CC (2014) Hydrothermal liquefaction of barks into bio-crude – Effects of species and ash content/composition. Fuel Volume 116: 214-220. https://doi.org/10.1016/j.fuel.2013.07.096.

Fernandes MF, Cardoso D, Queiroz LD de (2020) An updated plant checklist of the Brazilian Caatinga seasonally dry forests and woodlands reveals high species richness and endemism. J. Arid Environ. Volume 174, article id 104079. https://doi.org/10.1016/j.jaridenv.2019.104079.

Ferreira-Leitão V, Gottschalk LMF, Ferrara MA, Nepomuceno AL, Molinari HBC, Bon EPS (2010) Biomass residues in Brazil: Availability and potential uses. Waste Biomass Valor. 1, 65-76. https://doi.org/10.1007/s12649-010-9008-8.

Field, CB, Campbell JE, Lobell DB (2008) Biomass energy: The scale of the potential resource. Trends Ecol. Evol. 23(2): 65-72. https://doi.org/10.1016/j.tree.2007.12.001.

Finnish Ministry of Agriculture and Forestry (2005) Peltoviljelyn tulevaisuuden linjaukset Suomessa. Memorandum 15/2005 of The Ministry of Agriculture and Forestry. https://julkaisut.valtioneuvosto.fi/items/2a358958-3f47-4d31-93fa-cd7252bda9fc. [in Finnish].

Frombo F, Minciardi R, Robba M, Sacile R (2009) A decision support system for planning biomass-based energy production. Energy 34(3): 362-369. https://doi.org/10.1016/j.energy.2008.10.012.

Funke A, Ziegler F (2010) Hydrothermal carbonization of biomass: A summary and discussion of chemical mechanisms for process engineering. Biofuels, Bioprod. Bioref., 4: 160-177. https://doi.org/10.1002/bbb.198.

Furley PA, Ratter JA (1988) Soil resources and plant communities of the central Brazilian Cerrado and their development. J. Biogeogr. 15(1): 97-108. https://doi.org/10.2307/2845050.

Gama JRV, Souza ALD, Silva MLD, Vieira DDS, Oliveira MLRD, Figueiredo AES, Lafetá, BO (2022) Financial viability of charcoal production in different forest management systems in Brazil. Rev. For. Mesoam. Kurú 19(44): 12-20. http://dx.doi.org/10.18845/rfmk.v19i44.6096.

Gerssen-Gondelach SJ, Saygin D, Wicke B, Patel MK, Faaij APC (2014) Competing uses of biomass: Assessment and comparison of the performance of bio-based heat, power, fuels and materials. Renew. Sustain. Energy Rev. Volume 40: 964-998. https://doi.org/10.1016/j.rser.2014.07.197.

González-Arias J, Sánchez ME, Cara-Jiménez J, Baena-Moreno FM, Zhang Z (2022) Hydrothermal carbonization of biomass and waste: A review. Environ. Chem. Lett. 20, 211–221. https://doi.org/10.1007/s10311-021-01311-x.

González-García S, Mola-Yudego B, Dimitriou I, Aronsson P, Murphy R (2012) Environmental assessment of energy production based on long term commercial willow plantations in Sweden. Sci. Total Environ. Volumes 421-422: 210-219. https://doi.org/10.1016/j.scitotenv.2012.01.041.

González-García S, Teresa Moreira M, Cláudia Dias A, Mola-Yudego B (2014) Cradle-to-gate Life Cycle Assessment of forest operations in Europe: environmental and energy profiles. J. Clean. Prod. Volume 66: 188-198. https://doi.org/10.1016/j.jclepro.2013.11.067.

Haldar D, Shabbirahmed AM, Singhania RR, Chen CW, Dong CD, Vinoth Kumar P, Patel AK (2022) Understanding the management of household food waste and its engineering for sustainable valorization- A state-of-the-art review. Bioresour. Technol. Volume 358, article id 127390. https://doi.org/10.1016/j.biortech.2022.127390.

Haridasan M (1982) Aluminium accumulation by some Cerrado native species of central Brazil. Plant Soil 65(2): 265-273. http://www.jstor.org/stable/42933929.

Harisankar S, Vishnu Mohan R, Choudhary V, Vinu R (2022) Effect of water quality on the yield and quality of the products from hydrothermal liquefaction and carbonization of rice straw. Bioresour. Technol. Volume 351, article id 127031. https://doi.org/10.1016/j.biortech.2022.127031.

Hayes DJM (2012) Development of near infrared spectroscopy models for the quantitative prediction of the lignocellulosic components of wet *Miscanthus* samples. Bioresour. Technol. Volume 119: 393-405. https://doi.org/10.1016/j.biortech.2012.05.137.

Hedayati Marzbali M, Kundu S, Halder P, Patel S, Hakeem IG, Paz-Ferreiro J, Madapusi S, Surapaneni A, Shah K (2021) Wet organic waste treatment via hydrothermal processing: A critical review. Chemosphere Volume 279, article id130557. https://doi.org/10.1016/j.chemosphere.2021.130557.

Heidari M, Dutta A, Acharya B, Mahmud S (2019) A review of the current knowledge and challenges of hydrothermal carbonization for biomass conversion. J. Energy Inst. 92(6), p. 1779-1799. https://doi.org/10.1016/j.joei.2018.12.003.

Helsinki: Natural Resources Institute Finland [referred: 27.03.2025]. https://www.luke.fi/en/statistics/wood-consumption/wood-pellets-2024. Accessed 15 January 2026.

Hernández-Neri N, Gutiérrez-Antonio C, García-Trejo JF, Feregrino-Pérez AA, Toledano-Ayala M (2022) Valorization of rice husks and bean straws through fuel pellets production: An experimental and modelling approach. Rev. Mex. Ing. Quím. 21, article id 22679. https://doi.org/10.24275/rmiq/Alim2679.

Hijosa-Valsero M, Garita-Cambronero J, Paniagua-García AI, Díez-Antolínez R (2018). Biobutanol production from coffee silverskin. Microb. Cell Fact. 17, 154. https://doi.org/10.1186/s12934-018-1002-z.

Hoffmann WA, Geiger EL, Gotsch SG, Rossatto DR, Silva LCR, Lau OL, Haridasan M, Franco AC (2012) Ecological thresholds at the savanna-forest boundary: how plant traits, resources and fire govern the distribution of tropical biomes. Ecol Lett 15: 759-768. https://doi.org/10.1111/j.1461-0248.2012.01789.x.

Hofmann GS, Weber EJ, Bastazini VAG, Rossatto DR, Franco AC, Granada CE, Kaminski LA, Ubaid FK, Leandro-Silva V, Borges-Martins M, Silva RC, Cardoso MF, Oliveira LFB, Aquino FE, Pereira MJR (2025) Climate change in the Brazilian Cerrado: A looming threat to terrestrial biodiversity. Wiley Interdiscip. Rev.: Clim. Change 16, no. 5, article id e70022. https://doi.org/10.1002/wcc.70022.

Holvoet J, Eichhorn MP, Giannetti F, Kükenbrink D, Liang X, Mokroš M, Novotný J, Pitkänen TP, Puliti S, Skudnik M, Stereńczak K, Terryn L, Vega C, Torresan C (2025) Terrestrial and mobile laser scanning for national forest inventories: From theory to implementation. Remote Sens. Environ. Volume 329, article id 114947. https://doi.org/10.1016/j.rse.2025.114947.

Hu Y, Feng S, Xu C, Bassi A (2017) Production of low-nitrogen bio-crude oils from microalgae pre-treated with pre-cooled NaOH/urea solution. Fuel Volume 206: 300-306. https://doi.org/10.1016/j.fuel.2017.06.021.

Imatomi M, Novaes P, Matos AP, Gualtieri SCJ, Molinillo JMG, Lacret R, Varela RM, Macías FA (2013) Phytotoxic effect of bioactive compounds isolated from *Myrcia tomentosa* (Myrtaceae) leaves. Biochem. Syst. Ecol. 46: 29-35. https://doi.org/10.1016/j.bse.2012.09.005.

Instituto Brasileiro de Geografia e Estatística (IBGE) (2006) Sistematização das Informações sobre Recursos Naturais Mapa de Biomas do Brasil Data: Novembro, https://www.ibge.gov.br/. [in Portuguese].

Instituto Brasileiro de Geografia e Estatística (IBGE) (2019) Biomas e sistema costeiro-marinho do Brasil: compatível com a escala 1:250 000/ IBGE. Coordenação de Recursos Naturais e Estudos Ambientais. Série Relatórios metodológicos v. 45. Rio de Janeiro. https://biblioteca.ibge.gov.br/index.php/biblioteca-catalogo?view=detalhes&id=2101676. [in Portuguese].

International Energy Agency (IEA) (2021) Country Reports: Implementation of bioenergy in Brazil - 2021 update. https://www.ieabioenergy.com/wp-content/uploads/2021/11/CountryReport2021_Brazil_final.pdf. Accessed 10 July 2024.

International Energy Agency (IEA) (2024a) Country Reports: Implementation of bioenergy in Brazil - 2024 update. https://www.ieabioenergy.com/wp-content/uploads/2024/12/CountryReport2024_Brazil_final.pdf. Accessed 30 November 2025.

International Energy Agency (IEA) (2024b) Country Reports: Implementation of bioenergy in Finland - 2024 update. https://www.ieabioenergy.com/wp-content/uploads/2024/12/CountryReport2024_Finland_final.pdf. Accessed 30 November 2025.

International Energy Agency (IEA) (2024c) Country Reports: Implementation of bioenergy in Sweden - 2024 update. https://www.ieabioenergy.com/wp-content/uploads/2024/12/CountryReport2024_Sweden_final.pdf. Accessed 30 November 2025.

International Energy Agency (IEA) (2024d) What is bioenergy? Factsheet. https://www.ieabioenergy.com/wp-content/uploads/2024/12/IEA-Bioenergy_Factsheet-1-1.pdf. Accessed 6 May 2026.

International Organization for Standardization (2010) Reaction to fire tests for products - Determination of the gross heat of combustion (calorific value), ISO 1716:2010, Geneva, Switzerland.

International Organization for Standardization. (2020) ISO 1928:2020 Coal and coke – Determination of gross calorific value. Measurement standard. Geneva, Switzerland.

Jasinskas A, Šarauskisand E, Domeika R (2014) Technological evaluation of non-traditional energy plant cultivation and utilization for energy purposes in Lithuania, Proceedings International Conference of Agricultural Engineering; 06-10, Switzerland European Society for Agricultural Engineers (EURAGENG), Zurich.

Jena U, Das KC, Kastner JR (2011) Effect of operating conditions of thermochemical liquefaction on biocrude production from Spirulina platensis. Bioresour. Technol. 102(10): 6221-6229. https://doi.org/10.1016/j.biortech.2011.02.057.

Jiang Z, Lou Y, Liu X, Sun W, Wang H, Liang J, Guo J, Li N, Yang Q (2023) Combined application of coffee husk compost and inorganic fertilizer to improve the soil ecological environment and photosynthetic characteristics of Arabica coffee. Agronomy 13(5):1212. https://doi.org/10.3390/agronomy13051212.

Jokinen N, Eronen E, Salami A, Hyttinen M, Jänis J, Vepsäläinen J, Lappalainen R, Tomppo L (2023) Valorization potential of the aqueous products from hydrothermal liquefaction and stepwise slow pyrolysis of wood bark and hemp hurds with yields and product comparison.

Bioresour. Technol. Rep. Volume 21, article id 101385. https://doi.org/10.1016/j.biteb.2023.101385.

Jokinen N, Eronen E, Vepsäläinen J, Jänis J, Lappalainen R, Tomppo L, Tynkkynen T (2024) 17O NMR spectroscopy protocol for the determination of water content in liquids produced by pyrolysis and hydrothermal liquefaction. Anal. Chim. Acta Volume 1329, article id 343188. https://doi.org/10.1016/j.aca.2024.343188.

Jolly WM, Cochrane MA, Freeborn PH, Holden ZA, Brown TJ, Williamson GJ, Bowman DMJS (2015) Climate-induced variations in global wildfire danger from 1979 to 2013. Nat. Commun. 6, article id 7537. https://doi.org/10.1038/ncomms8537.

Kaliyan N, Vance Morey R (2009) Factors affecting strength and durability of densified biomass products. Biomass Bioenergy 33(3): 337-359. https://doi.org/10.1016/j.biombioe.2008.08.005.

Kamgang Nzekoue F, Borsetta G, Navarini L, Abouelenein D, Xiao J, Sagratini G, Vittori S, Caprioli G, Angeloni S (2022) Coffee silverskin: Characterization of B-vitamins, macronutrients, minerals and phytosterols. Food Chem. Volume 372, article id131188. https://doi.org/10.1016/j.foodchem.2021.131188.

Kardung M, Cingiz K, Costenoble O, Delahaye R, Heijman W, Lovrić M, van Leeuwen M, M'Barek R, van Meijl H, Piotrowski S, Ronzon T, Sauer J, Verhoog D, Verkerk PJ, Vrachioli M, Wesseler JHH, Zhu BX (2021) Development of the circular bioeconomy: Drivers and indicators. Sustainability 13(1):413. https://doi.org/10.3390/su13010413.

Kataki R, Konwer D (2001) Fuelwood characteristics of some indigenous woody species of north-east India. Biomass Bioenergy 20(1): 17-23. https://doi.org/10.1016/S0961-9534(00)00060-X.

Kiran Kumar P, Saranga VK, Verma K, Kandimalla P, Dheravath B, Srilatha K, Himabindu V (2018) Bio oil production from microalgae via hydrothermal liquefaction technology under subcritical water conditions. J. Microbiol. Methods Volume 153-117. https://doi.org/10.1016/j.mimet.2018.09.014.

Kraszkiewicz A, Przywara A, Parafiniuk S (2022) Emission of Nitric Oxide during the Combustion of various forms of solid biofuels in a low-power heating device. Energies 15(16), article id 5960. https://doi.org/10.3390/en15165960.

Kresna MS, Windy R, Suci AP, Bovi WH (2024) Characteristics of Arabica and Robusta spent coffee grounds oil extract with different solvents. IOP Conf. Ser.: Earth Environ. Sci. 1379, article id 012035. DOI 10.1088/1755-1315/1379/1/012035.

Kulkarni RM, Mentha SS, R A, Mascarenhas EW, Polavarapu S, Appaiah T (2024) Valorization of waste coffee silverskin as a source of antioxidant by extraction with agitation. Environm. Qual. Manag. 34, article id e22209. https://doi.org/10.1002/tqem.22209.

Lachos-Perez D, Torres-Mayanga PC, Abaide ER, Zabot GL, Castilhos F de (2022) Hydrothermal carbonization and liquefaction: differences, progress, challenges, and opportunities. Bioresour. Technol. Volume 343, article id 126084. https://doi.org/10.1016/j.biortech.2021.126084.

Larsson S, Lindegaard K (2003) Full scale implementation of short rotation willow coppice, SRC, in Sweden, Agrobränsle AB, Örebro, Sweden.

La Torre Ugarte DG de, Langholtz MH, Hellwinckel CM (2026) Markets mitigate land-use competition from energy crops and increase farm revenues. Appl. Econ. Perspect. Policy Volume 48(3): 1-13. https://doi.org/10.1002/aepp.70051.

Leal IR, Silva JMC da, TabareliI M, Lacher TE Jr. (2005) Changing the course of biodiversity conservation in the Caatinga of Northeastern Brazil. Conserv. Biol. 19: 701-706. https://doi.org/10.1111/j.1523-1739.2005.00703.x.

Leal NRF, Vieira Vigliano M, Pinto FA, Sousa TV de, Velozo LSM, Sabino KCC, Graça Justo M da, Pinto Coelho MG (2018) Anti-inflammatory effect of diterpenes-enriched fractions from *Pterodon polygalaeflorus* through inhibition of macrophage migration and cytokine production. J. Pharm. Pharmacol. 70: 808-820. https://doi.org/10.1111/jphp.12889.

Lee Y-G, Cho E-J, Maskey S, Nguyen D-T, Bae H-J (2023) Value-added products from coffee waste: A review. Molecules 28(8):3562. https://doi.org/10.3390/molecules28083562.

Lehtikangas P (2001) Quality properties of pelletised sawdust, logging residues and bark. Biomass Bioenergy 20(5): 351-360. https://doi.org/10.1016/S0961-9534(00)00092-1.

Lemus R, Lal R (2005) Bioenergy crops and carbon sequestration. Crit. Rev. Plant Sci. 24:1: 1-21. https://doi.org/10.1080/07352680590910393.

Leng L, Yuan X, Huang H, Shao J, Wang H, Chen X, Zeng G (2015) Bio-char derived from sewage sludge by liquefaction: Characterization and application for dye adsorption. Applied Surface Science Volume 346: 223-231. https://doi.org/10.1016/j.apsusc.2015.04.014.

Leon M, Garcia AN, Marcilla A, Martinez-Castellanos I, Navarro R, Catala L (2018) Thermochemical conversion of animal by-products and rendering products. Waste Management Volume 73, pp. 447-463. https://doi.org/10.1016/j.wasman.2017.08.010.

Lewandowski I, Faaij APC (2006) Steps towards the development of a certification system for sustainable bio-energy trade. Biomass Bioenergy 30(2): 83-104. https://doi.org/10.1016/j.biombioe.2005.11.003.

Lewandowski I, Scurlock JMO, Lindvall E, Myrsini Christou M (2003) The development and current status of perennial rhizomatous grasses as energy crops in the US and Europe. Biomass Bioenergy 25(4): 335-361. https://doi.org/10.1016/S0961-9534(03)00030-8.

Lima TL de, Silva JAA da, Longhi RV, Gallo R, Hakamada RE, Santos MVF dos, Martínez Molina JR, Herrera Machuca MÁ, Muir JP, Ferreira RLC (2021) Structure, survival, and species diversity in a tropical dry forest submitted to coppicing. For. Ecol. Manag. Volume 2021;501, article id 119700. https://doi.org/10.1016/j.foreco.2021.119700.

Lindley JA, Vossoughi M (1989) Physical properties of biomass briquettes. Trans. ASAE 32: 361-366. DOI: 10.13031/2013.31010.

Lio L da, Bortolus M, Canu P (2025) Emissions reduction from wood pellet stoves by uniform feeding. Renewable Energy Volume 242, article id 122273. https://doi.org/10.1016/j.renene.2024.122273.

Lubwama M, Yiga VA, Ssempijja I, Lubwama HN (2023) Thermal and mechanical characteristics of local firewood species and resulting charcoal produced by slow pyrolysis. Biomass Conv. Bioref. 13: 6689-6704. https://doi.org/10.1007/s13399-021-01840-z.

Luo Z, Zhou J (2025) Thermal Conversion of Biomass. In: Lackner, M., Sajjadi, B., Chen, WY. (eds) Handbook of climate change mitigation and adaptation. Springer, Cham. https://doi.org/10.1007/978-3-031-84483-6_27.

Magiera T, Heikkilä P, Lukkari S, Bućko MS, Szuszkiewicz MM (2025) Environmental impact of three distinct combustion products released from domestic heating installations operating on wood and non-wood pellets. Atmos. Environ. Volume 359, article id 121393. https://doi.org/10.1016/j.atmosenv.2025.121393.

Manyatsha K, Hattingh BB, Edokpayi J (2025) First study on the characterization of preferred fuelwood species for various energy applications in Limpopo Province. Sci. Afr. Volume 30, article id e03062. https://doi.org/10.1016/j.sciaf.2025.e03062.

MapBiomas - Brazil Collection 10 Infographics on Land Cover. https://brasil.mapbiomas.org/en/infograficos/. Accessed 26 November 2025. Accessed 8 April 2021.

Marques MMG (2006) Geoestatística Aplicada Na análise biométrica Dos Montados de sobreira e Azinheira. Technical University of Lisbon, Lisboa, Portugal, p 163. DOI: 10.13140/RG.2.1.2178.5761. [in Portuguese].

Marques RD, Cunha TQG, Chagas MP, Venturoli F, Belini GB, Yamaji FM, Sette Junior CR (2020) Wood quality of five species of the Cerrado for energy purposes. Sci. For. 48(125), article id e3225. https://doi.org/10.18671/scifor.v48n125.11.

Mehmood MA, Ibrahim M, Rashid U, Nawaz M, Ali S, Hussain A, Gull M (2017) Biomass production for bioenergy using marginal lands. Sustain. Prod. Consum. Volume 9: 3-21. https://doi.org/10.1016/j.spc.2016.08.003.

Młynarczykowska A, Orlof-Naturalna M (2024) Biosorption of copper (II) ions using coffee grounds - A case study. Sustainability 16(17), article id 7693. https://doi.org/10.3390/su16177693.

Mola-Yudego B, González-Olabarria JR (2010) Mapping the expansion and distribution of willow plantations for bioenergy in Sweden: Lessons to be learned about the spread of energy crops. Biomass Bioenergy Volume 34, Issue 4: 442-448. https://doi.org/10.1016/j.biombioe.2009.12.008.

Myers N, Mittermeier RA, Mittermeier CG, Fonseca GABD, Kent J (2000) Biodiversity hotspots for conservation priorities. Nature 403: 853-858. https://doi.org/10.1038/35002501.

Ministry of Economic Affairs and Employment of Finland (2022) Carbon neutral Finland 2035 – national climate and energy strategy, Helsinki, Finland. https://tem.fi/en/energy-and-climate-strategy. Accessed 20 November 2025.

Mirzoyan S, Aghekyan H, Vanyan L, Vassilian A, Trchounian K (2022) Coffee silverskin as a substrate for biobased production of biomass and hydrogen by *Escherichia coli*. Int. J. Energy Res. 46(15): 23110-23121. https://doi.org/10.1002/er.8612.

Mohan O, Fakayode OA, Kumar A (2025) Biofuel production from pipeline-transported lignocellulosic biomass via hydrothermal liquefaction: Process optimization and product characterization. Biomass Bioenergy Volume 202, article id 108210. https://doi.org/10.1016/j.biombioe.2025.108210.

Munawar MA, Khoja AH, Naqvi SR, Taqi Mehran M, Hassan M, Liaquat R, Dawood UF (2021) Challenges and opportunities in biomass ash management and its utilization in novel applications. Renew. Sustain. Energy Rev. Volume 150, article id 111451. https://doi.org/10.1016/j.rser.2021.111451.

Muscat A, Olde EM de, Ripoll-Bosch R Van Zanten HHE, Metze TAP, Termeer CJAM, Van Ittersum MK, De Boer IJM (2021) Principles, drivers and opportunities of a circular bioeconomy. Nature Food 2: 561-566. https://doi.org/10.1038/s43016-021-00340-7.

Mussatto SI, Machado EMS, Carneiro LM, Teixeira JA (2012) Sugars metabolism and ethanol production by different yeast strains from coffee industry wastes hydrolysates. Appl. Energy Volume 92: 763-768. https://doi.org/10.1016/j.apenergy.2011.08.020.

Naik SN, Goud VV, Rout PK, Dalai AK (2010) Production of first and second generation biofuels: A comprehensive review. Renew. Sustain. Energy Rev. Volume 14, Issue 2: 578-597. https://doi.org/10.1016/j.rser.2009.10.003.

Nackley LL, Lieu VH, Garcia BB, Richardson JJ, Isaac E, Spies K, Rigdon S, Schwartz DT (2013) Bioenergy that supports ecological restoration. Front. Ecol. Environ. 11: 535-540. https://doi.org/10.1890/120241.

Nami Kartal S (2003) Removal of copper, chromium, and arsenic from CCA-C treated wood by EDTA extraction. Waste Manag. Volume 23(6): 537-546. https://doi.org/10.1016/S0956-053X(02)00143-5.

Narita Y, Inouye K (2014) Review on utilization and composition of coffee silverskin. Food Res. Int. Volume 61: 16-22. https://doi.org/10.1016/j.foodres.2014.01.023.

NatureServe (2021) NatureServe Explorer. NatureServe, Arlington, Virginia. https://explorer.natureserve.org/. Accessed 8 April 2021.

Nava-Bravo I, Escamilla-Alvarado C, Cano-Gómez JJ, Valencia-Vázquez R, Galván-Arzola U, Cuevas-García R (2025) Bio-crude and biochar production and properties from corn stover at low energy-intensive hydrothermal liquefaction. Biomass Conv. Bioref. 15: 11985-12000. https://doi.org/10.1007/s13399-024-05977-5.

Nazareno LSQ, Ribeiro A, Sousa MVC, Vieira CW, Ferraz Filho AC (2021) Wood volume estimation strategies for trees from a Dry Forest/Savannah transition area in Piauí, Brazil. South. For. 83(2): 111-119. https://doi.org/10.2989/20702620.2020.1862634.

Ngugi MR, Neldner VJ, Ryan S, Lewis T, Li J, Norman P, Mogilski M (2018) Estimating potential harvestable biomass for bioenergy from sustainably managed private native forests in Southeast Queensland, Australia. For. Ecosyst. 5, 6. https://doi.org/10.1186/s40663-018-0129-z.

Nijsen M, Smeets E, Stehfest E, Vuuren DP van (2012) An evaluation of the global potential of bioenergy production on degraded lands. Glob. Change Biol. Bioenergy 4: 130-147. https://doi.org/10.1111/j.1757-1707.2011.01121.x.

Nižetić S, Papadopoulos A, Radica G, Zanki V, Arıcı M (2019) Using pellet fuels for residential heating: A field study on its efficiency and the users' satisfaction. Energy and Build. Volume 184: 193-204. https://doi.org/10.1016/j.enbuild.2018.12.007.

Nunes AR, Moreira Rodrigues AL, Brito de Queiróz D, Gusmão Pinto Vieira I, Câmara Neto JF, Tavares Calixto Junior J, Relison Tintino S, Maia de Morais S, Douglas Melo Coutinho H (2018) Photoprotective potential of medicinal plants from Cerrado biome (Brazil) in relation to phenolic content and antioxidant activity. J. Photochem. Photobiol. B: Biol. 189, 119-123. https://doi.org/10.1016/j.jphotobiol.2018.10.013.

Oleszek M, Matyka M (2020) Energy use efficiency of biogas production depended on energy crops, nitrogen fertilization level, and cutting system. Bioenergy Resources 13(4):1069-1081. https://doi.org/10.1007/s12155-020-10147-2.

Oliveira VRD, Ribeiro A, Pareyn FGC, Drumond MA, Porto DD, Kiill LHP, Ferraz Filho AC (2023) The influence of clear-cut area size on forest regrowth: a case study in the dry tropical forests of Pernambuco, Brazil. CERNE 29, article id e–103165. https://doi.org/10.1590/01047760202329013165.

Ostwald M, Jonsson A, Wibeck V, Asplund T (2013) Mapping energy crop cultivation and identifying motivational factors among Swedish farmers. Biomass Bioenergy Volume 50: 25-34. https://doi.org/10.1016/j.biombioe.2012.09.058.

Özdenkçi K, De Blasio C, Muddassar HR, Melin K, Oinas P, Koskinen J, Sarwar G, Mika Järvinen M (20217) A novel biorefinery integration concept for lignocellulosic biomass. Energy Convers. Manag. Volume 149: 974-987. https://doi.org/10.1016/j.enconman.2017.04.034.

Pahkala K, Aalto M, Isolahti M, Poikola J, Jauhiainen L (2008) Large-scale energy grass farming for power plants—A case study from Ostrobothnia, Finland. Biomass Bioenergy Volume 32, Issue 11: 1009-1015. https://doi.org/10.1016/j.biombioe.2008.02.004.

Paine LK, Peterson T,Undersander DJ, Rineer KC, Bartelt GA, Temple SA, Sample DV, Klemme RM (1996) Some ecological and socio-economic considerations for biomass energy crop production. Biomass Bioenergy Volume 10, Issue 4: 231-242. https://doi.org/10.1016/0961-9534(95)00072-0.

Paz MD, Phother-Simon J, Andersson S, Jonsson T (2021) High temperature corrosion memory in a waste fired boiler – Influence of sulfur. Waste Manag. Volume 130: 30-37. https://doi.org/10.1016/j.wasman.2021.05.005.

Petlickaitė R, Jasinskas A, Domeika R, Pedišius N, Lemanas E, Praspaliauskas M, Kukharets S (2023) Evaluation of the processing of multi-crop plants into pelletized biofuel and its use for energy conversion. Processes11(2):421. https://doi.org/10.3390/pr11020421.

Pfluger RA (1975) Solid wastes: origin, collection, processing, and disposal, Wiley Interscience, New York, NY, USA.

Pham HD, Shelley T, Burey PP, Feldman J, Andreas Helwig A (2025) Hydrothermal liquefaction: A promising technology for renewable energy and environmental clean-up applications. Biomass Bioenergy Volume 201, article id 108151. https://doi.org/10.1016/j.biombioe.2025.108151.

Pinho R, Oliveira M, Mendes Teixeira BM, Silva Borges AD da (2025) Evaluating quality and price dynamics of wood pellets in the Portuguese market: Impacts of geopolitical and economic factors. Energy Strategy Rev. Volume 59, article id 101719. https://doi.org/10.1016/j.esr.2025.101719.

Posmanik R, Cantero DA, Malkani A, Sills DL, Tester JW (2017) Biomass conversion to bio-oil using sub-critical water: Study of model compounds for food processing waste. J. Supercrit. Fluids Volume 119: 26-35. https://doi.org/10.1016/j.supflu.2016.09.004.

Pourfarzad A, Mahdavian-Mehr H, Sedaghat N (2013) Coffee silverskin as a source of dietary fiber in bread-making: Optimization of chemical treatment using response surface methodology. LWT - Food Sci. Technol. Volume 50, Issue 2: 599-606. https://doi.org/10.1016/j.lwt.2012.08.001.

Pozo C del, Rego F, Yang Y, Puy N, Bartrolí J, Fàbregas E, Bridgwater AV (2021) Converting coffee silverskin to value-added products by a slow pyrolysis-based biorefinery process. Fuel Process. Technol. Volume 214, article id 106708. https://doi.org/10.1016/j.fuproc.2020.106708.

Prade T, Finell M, Svensson SE, Mattsson JE (2012) Effect of harvest date on combustion related fuel properties of industrial hemp (*Cannabis sativa* L.). Fuel Volume 102: 592-604. https://doi.org/10.1016/j.fuel.2012.05.045.

Prado D (2003) As caatingas da América do Sul, in Leal IR, Tabarelli M, Silva JMC, editors, Ecologia e conservação da Caatinga. Editora Universitária, Universidade Federal de Pernambuco, Recife, Brasil, pp 3-73. https://www.gov.br/mma/pt-br/assuntos/biodiversidade-e-biomas/biomas-e-ecossistemas/biomas/arquivos-biomas/5_livro_ecologia_e_conservao_da_caatinga_203.pdf. [in Portuguese].

Proskurina S, Alakangas E, Heinimö J, Mikkilä M, Vakkilainen E (2017) A survey analysis of the wood pellet industry in Finland: Future perspectives. Energy Volume 118, 692-704. https://doi.org/10.1016/j.energy.2016.10.102.

Qiu H, Yan J, Lei Z, Sun D (2018) Rising wages and energy consumption transition in rural China. Energy Policy 119: 545-553. https://doi.org/10.1016/j.enpol.2018.04.053.

Rafael L, Herrero-Davila L, Campelo JM, Clark JH, Hidalgo JM, Luna D, Marinas JM, Romero AA (2008) Biofuels: a technological perspective. Energy Environ. Sci. 1: 542-64. https://doi.org/10.1039/B807094F.

Rajão R, Soares-Filho B, Nunes F, Börner J, Machado L, Assis D, Oliveira A, Pinto L, Ribeiro V, Rausch L, Gibbs H, Figueira D (2020) The rotten apples of Brazil's agribusiness. Science 369(6501): 246-248. https://doi.org/10.1126/science.aba6646.

Rämö AK, Järvinen E, Latvala T, Toivonen R, Silvennoinen H (2009) Interest in energy wood and energy crop production among Finnish non-industrial private forest owners. Biomass Bioenergy Volume 33, Issue 9: 1251-1257. https://doi.org/10.1016/j.biombioe.2009.05.013.

Rao U, Posmanik R, Hatch LE, Tester JW, Walker SL, Barsanti KC, Jassby D (2018) Coupling hydrothermal liquefaction and membrane distillation to treat anaerobic digestate from food and dairy farm waste. Bioresour. Technol. Volume 267: 408-415. https://doi.org/10.1016/j.biortech.2018.07.064.

Remijnse M, Rohmer SUK, Marandi A, Van Woensel T (2025) Optimising agri-food supply chains: Managing food waste through harvest and side-stream valorization. J. Clean. Prod. Volume 503, article id 145349. https://doi.org/10.1016/j.jclepro.2025.145349.

Ribeiro A, Ferraz Filho AC, Farias SGG de, Dias BAS, Silva HP da (2021) Restoration potential of eight tree species from a seasonally dry tropical forest in southeast Piauí, Brazil. CERNE 27, article id e–102702. https://doi.org/10.1590/01047760202127012702.

Ribeiro RA, Rodrigues FM (2006) Genética da conservação em espécies vegetais do cerrado. R. Ci. méd. biol., Salvador, v. 5, n. 3: 253-260, set. /dez. https://repositorio.ufba.br/handle/ri/20465. [in Portuguese].

Rogmans M (2010) inventor; Conpower Energie GmbH and Co KG, assignee. *Fallopia* plant named ‘IGNISCUM’, United States Plant Patent USPP 21304P3, September.

Ross AB, Biller P, Kubacki ML, Li H, Lea-Langton A, Jones JM (2010) Hydrothermal processing of microalgae using alkali and organic acids. Fuel Volume 89, Issue 9: 2234-2243. https://doi.org/10.1016/j.fuel.2010.01.025.

Ruiz HA, Galbe M, Garrote G, Ramirez-Gutierrez DM, Ximenes E, Sun SN, Lachos-Perez S, Rodríguez-Jasso RM, Sun RC, Yang B, Ladisch MR (2021) Severity factor kinetic model as a strategic parameter of hydrothermal processing (steam explosion and liquid hot water) for biomass fractionation under biorefinery concept. Bioresour. Technol. Volume 342, article id 125961. https://doi.org/10.1016/j.biortech.2021.125961.

Saenger M, Hartge EU, Werther J, Ogada T, Siagi Z (2001) Combustion of coffee husks. Renewable Energy Volume 23, Issue 1: 103-121. https://doi.org/10.1016/S0960-1481(00)00106-3.

Sampaio G, Nobre C, Costa MH, Satyamurty P, Soares-Filho BS, Cardoso M (2007) Regional climate change over eastern Amazonia caused by pasture and soybean cropland expansion. Geophys. Res. Lett. 34, article id L17709. DOI: 10.1029/2007GL030612.

Sano EE, Ferreira LG, Asner GP, Steinke ET (2007) Spatial and temporal probabilities of obtaining cloud-free Landsat images over the Brazilian tropical savanna. Int. J. Remote Sens. 28(12): 2739-2752. https://doi.org/10.1080/01431160600981517.

Santos JC, Leal IR, Almeida-Cortez JS, Fernandes GW, Tabarelli M (2011) Caatinga: the scientific negligence experienced by a dry tropical forest. Trop. Conserv. Sci. 4(3): 276-286. DOI:10.1177/194008291100400306.

Scarlat N, Dallemand JF, Monforti-Ferrario F, Nita V. The role of biomass and bioenergy in a future bioeconomy: Policies and facts. Env. Dev. Volume 15, 2015: 3-34. https://doi.org/10.1016/j.envdev.2015.03.006.

Schmidt IB, Eloy L (2020) Fire regime in the Brazilian Savanna: Recent changes, policy and management. Flora Volume 268, article id 151613. https://doi.org/10.1016/j.flora.2020.151613.

Selkimäki M, Mola-Yudego B, Röser D, Prinz R, Sikanen L (2010) Present and future trends in pellet markets, raw materials, and supply logistics in Sweden and Finland. Renew. Sustain. Energy Rev. Volume 14, Issue 9: 3068-3075. https://doi.org/10.1016/j.rser.2010.06.009.

Seppälä M, Laine A, Rintala J (2013) Screening of novel plants for biogas production in northern conditions. Bioresour. Technol. 139: 355-362. 10.1016/j.biortech.2013.04.014.

Serviço Florestal Brasileiro (SFB) (2023) Data concerning National Forest Inventory in the Cerrado Biome. https://snif.florestal.gov.br/.

Severo dos Santos JF, Naval LP (2022) Soy water footprint and socioeconomic development: An analysis in the new agricultural expansion areas of the Brazilian Cerrado (Brazilian savanna). Environmental Development Volume 42, article id 100670. https://doi.org/10.1016/j.envdev.2021.100670.

SFS Finnish Standards (2007) SFS-EN ISO 10304-1:2007 Water quality - Determination of dissolved anions by liquid chromatography of ions, Part 1: Determination of bromide, chloride, fluoride, nitrate, nitrite, phosphate and sulfate (ISO 10304-1:2007), Measurement standard, Helsinki, Finland.

SFS Finnish Standards (2011) SFS-EN 15408:2011 Solid recovered fuels, Methods for the determination of sulphur (S), chlorine (Cl), fluorine (F) and bromine (Br) content, Measurement standard, Helsinki, Finland.

SFS Finnish Standards (2021) SFS-ISO 17225-4:2021, Solid biofuels, Fuel specifications and classes - Part 4: Graded wood chips, Helsinki, Finland.

SFS Finnish Standards (2014) SFS-EN ISO 17225-6:2014 Solid Biofuels - Fuel specifications and classes, Part 6: Graded non-woody pellets, Measurement standard, Helsinki, Finland.

SFS Finnish Standards (2015) SFS-EN ISO 18122:2015 Solid Biofuels - Determination of ash content, Measurement standard, Helsinki, Finland.

SFS Finnish Standards (2015) SFS-EN ISO 18123:2015 Solid Biofuels - Determination of the volatile matter, Measurement standard, Helsinki, Finland.

SFS Finnish Standards (2017) SFS-EN ISO 18125:2017 Solid biofuels. Determination of calorific value, Measurement standard, Helsinki, Finland.

Shen T, Qi H, Ma H, Xie H, Gnanasekaran L, Vasseghian Y, Xia C (2025) Pyrolysis behavior and kinetics of grape pruning residues: Insights from multistep reaction models and Py-GC/MS. J. Anal. Appl. Pyrolysis Volume 186, article id 106899. https://doi.org/10.1016/j.jaap.2024.106899.

Silva TA, Aguiar do Couto E de, Assemany PP, Costa PAC, Marques PASS, Paradela F, Reis AJDD, Calijuri ML (2024) Biofuel from wastewater-grown microalgae: A biorefinery approach using hydrothermal liquefaction and catalyst upgrading. J. Environ. Manag. Volume 368, article id 122091. https://doi.org/10.1016/j.jenvman.2024.122091.

Silva Santos DW da, Stepka TF, Hess AF (2026) Spatial distribution patterns and horizontal structure of commercial tree species in the Tapajós-Arapiuns Extractive Reserve, Brazilian Amazon. Small-scale For. 25, 79-98. https://doi.org/10.1007/s11842-025-09612-7.

Simon MF, Grether R, Queiroz LP de, Skema C, Pennington RT, Hughes CE (2009) Recent assembly of the Cerrado, a neotropical plant diversity hotspot, by in situ evolution of adaptations to fire. Proc. Natl. Acad. Sci. U.S.A. 106 (48): 20359-20364. https://doi.org/10.1073/pnas.0903410106.

Slepetys J, Kadžiulienė Ž, Sarunaite L, Tilvikiene V, Kryzeviciene A (2012) Biomass potential of plants grown for bioenergy production. International scientific conference Renewable Energy and Energy Efficiency, pp 66-67.

Soares-Filho B, Rajão R, Macedo M, Carneiro A, Costa W, Coe M, Rodrigues H, Alencar A (2024) Cracking Brazil's Forest Code. Science 344: 363-364. https://doi.org/10.1126/science.1246663.

Soliño M, Oviedo JL, Caparrós A (2018) Are forest landowners ready for woody energy crops? Preferences for afforestation programs in Southern Spain. Energy Econ. Volume 73: 239-247. https://doi.org/10.1016/j.eneco.2018.05.026.

Souza AP, Costa FCP, Alencar RF, Lima SFB (2018) Exploração e utilização do potencial madeireiro da Caatinga no município de Aurora-estado do Ceará. Pesquisa e Ensino em Ciências Exatas e da Natureza v. 2, n. 2: 158-168. https://doi.org/10.29215/pecen.v2i2.1070. [in Portuguese].

Souza GM, Ballester MVR, Brito Cruz CH de, Chum H, Dale B, Dale VH, Fernandes ECM, Foust T, Karp A, Lynd L, Maciel Filho R, Milanez A, Nigro F, Osseweijer P, Verdade LM, Victoria RL, Wielen L van der (2017) The role of bioenergy in a climate-changing world. Environmental Development Volume 23: 57-64. https://doi.org/10.1016/j.envdev.2017.02.008.

Souza HJPL de, Muñoz F, Mendonça RT, Sáez K, Olave R, Segura C, Souza DPL de, Paula Protásio T de, Rodríguez-Soalleiro R (2021) Influence of lignin distribution, physicochemical characteristics and microstructure on the quality of biofuel pellets made from four different types of biomass. Renewable Energy Volume 163: 1802-1816. https://doi.org/10.1016/j.renene.2020.10.065.

Stolarski MJ, Krzyżaniak M, Olba-Zięty E (2025) Properties of pellets from forest and agricultural biomass and their mixtures. Energies 18(12). article id 3137. https://doi.org/10.3390/en18123137.

Strand J, Soares-Filho B, Costa MH, Oliveira U, Ribeiro SC, Pires GF, Oliveira A, Rajão R, May P, Hoff R van der, Siikamäki J, Motta RS da, Toman M (2018) Spatially explicit valuation of the Brazilian Amazon Forest's Ecosystem Services. Nat. Sustain. 1: 657-664. https://doi.org/10.1038/s41893-018-0175-0.

Streikus D, Jasinskas A, Domeika R, Čekanauskas S, Pedišius N, Vonžodas T, Annuk A (2017) Evaluation of Giant knotweed and *Miscanthus* as perspective energy plants and assessment of produced biofuel quality indicators, Proceedings of the 8th International Scientific Conference Rural Development; Nov 23-24, Aleksandras Stulginskis University, Akademija Lithuania. http://doi.org/10.15544/RD.2017.004.

Streimikiene D, Baležentis T, Volkov A, Morkūnas M, Žičkienė A, Streimikis J (2021) Barriers and Drivers of Renewable Energy Penetration in Rural Areas. Energies 14(20), article id 6452. https://doi.org/10.3390/en14206452.

Sustainable biofuels: prospects and challenges, The Royal Society, 2008, ISBN 978 0 85403 662 2.

Tan S, Kusumocahyo SP, Widiputri DI (2016) Pulverization of coffee silverskin extract as a source of antioxidant. IOP Conf. Ser.: Mater. Sci. Eng. 162 012027. DOI: 10.1088/1757-899X/162/1/012027.

Tekin K, Karagöz S, Bektaş S (2014) A review of hydrothermal biomass processing. Renew. Sustain. Energy Rev. Volume 40: 673-687. https://doi.org/10.1016/j.rser.2014.07.216.

Telmo C, Lousada J (2011) Heating values of wood pellets from different species. Biomass Bioenergy Volume 35, Issue 7, pp. 2634-2639. https://doi.org/10.1016/j.biombioe.2011.02.043.

Thomson Ek H, Singh J, Winberg J, Brady MV, Clough Y (2024) Farmers' motivations to cultivate biomass for energy and implications. Energy Policy Volume 193, article id 114295. https://doi.org/10.1016/j.enpol.2024.114295.

Ţîţei V, Andreoiu AC (2017) Perennial herbaceous species *Sida hermaphrodita* and *Polygonum sachalinense* for renewable and sustainable energy in the Republic of Moldova. Res. J. Agric. Sci. 49 (2): 53-60.

Tiwari R, Mallick N (2025) Process optimisation and scale-up of biocrude oil production through catalytic hydrothermal liquefaction utilising *Chlorella minutissima* biomass. Energy Volume 333, article id 137371. https://doi.org/10.1016/j.energy.2025.137371.

Trømborg E, Solberg B (2010) Forest sector impacts of the increased use of wood in energy production in Norway. For. Policy Econ. Volume 12, Issue 1: 39-47. https://doi.org/10.1016/j.forpol.2009.09.011.

Tsakalova M, Onorato C, Zoikis Karathanasis A, Deligkiozi I (2024) A circular economy framework for the assessment of bio-based value chains. Sustain. Chem. Environ. Volume 6, article id 100099. https://doi.org/10.1016/j.scenv.2024.100099.

Tsigkou K, Demissie BA, Hashim S, Ghofrani-Isfahani P, Thomas R, Mapinga KF, Kassahun SK, Angelidaki I (2025) Coffee processing waste: Unlocking opportunities for sustainable development. Renew. Sustain. Energy Rev. Volume 210, article id 115263. https://doi.org/10.1016/j.rser.2024.115263.

Tudge SJ, Murphy R, Harris ZM, De Palma A (2025) Balancing bioenergy expansion and restoration: Global shifts in biodiversity intactness. J. Appl. Ecol. 62: 1587-1596. https://doi.org/10.1111/1365-2664.14695.

Tumuluru JS (2018) Effect of pellet die diameter on density and durability of pellets made from high moisture woody and herbaceous biomass. Carbon Resour. Convers. Volume 1, Issue 1: 44-54. https://doi.org/10.1016/j.crcon.2018.06.002.

Tursi A (2019) A review on biomass: importance, chemistry, classification, and conversion. Biofuel Research Journal 22: 962-979. DOI: 10.18331/BRJ2019.6.2.3.

United States Department of Agriculture (USDA) (2023) Biofuels Annual, Brazil, Washington, D.C.

Uslu A, Faaij APC, Bergman PCA (2008) Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. Techno-economic evaluation of torrefaction, fast pyrolysis and pelletisation. Energy Volume 33, Issue 8: 1206-1223. https://doi.org/10.1016/j.energy.2008.03.007.

Yue D, You F, Snyder SW (2014) Biomass-to-bioenergy and biofuel supply chain optimization: Overview, key issues and challenges. Comput. Chem. Eng. Volume 66: 36-56. https://doi.org/10.1016/j.compchemeng.2013.11.016.

Yunusa SU, Narra S, Mensah E, Preko K, Saleh A (2024) Physical and thermochemical properties of selected wood species in Nigeria: A fuel suitability and pelleting potential assessment. Fuels 5(3): 261-277. https://doi.org/10.3390/fuels5030015.

Vardon DR, Sharma BK, Blazina GV, Rajagopalan K, Strathmann TJ (2012) Thermochemical conversion of raw and defatted algal biomass via hydrothermal liquefaction and slow pyrolysis. Bioresour. Technol. Volume 109: 178-187. https://doi.org/10.1016/j.biortech.2012.01.008.

Vassilev SV, Baxter D, Andersen LK, Vassileva CG, Morgan TJ (2012) An overview of the organic and inorganic phase composition of biomass. Fuel Volume 94: 1-33. https://doi.org/10.1016/j.fuel.2011.09.030.

Velozo LSM, Martino T, Vieira Vigliano M, Pinto FA, Silva GP, Graça A. Justo M da, Sabino KCC, Coelho MGP (2013) *Pterodon polygalaeflorus* essential oil modulates acute inflammation and B and T lymphocyte activation. Am. J. Chin. Med. 41(03): 545-563. https://doi.org/10.1142/S0192415X13500390.

Venendaal R, Jørgensen U, Foster CA (1997) European energy crops: A synthesis. Biomass Bioenergy Volume 13, Issue 3: 147-185. https://doi.org/10.1016/S0961-9534(97)00029-9.

Vourlitis GL, Dalmagro HJ, Pinto OB, Vieira RN, Malhado CRR, Arruda PHZ de (2026) Rapid recovery of Brazilian tropical savanna woodlands (Cerrado stricto sensu) to prescribed burns. Trees For. People Volume 23, article id 101129. https://doi.org/10.1016/j.tfp.2025.101129.

Vusić D, Vujanić F, Pešić K, Šafran B, Jurišić V, Zečić Ž (2021) Variability of normative properties of wood chips and implications to quality control. Energies 14(13), article id 3789. https://doi.org/10.3390/en14133789.

Zhao N, Liu Z, Yu T, Yan F (2024) Spent coffee grounds: Present and future of environmentally friendly applications on industries-A review. Trends Food Sci. Technol. Volume 143, article id 104312. https://doi.org/10.1016/j.tifs.2023.104312.

Zoccatelli G, Ciulu M (2025) Perspectives on the use of coffee silverskin in food formulations. J. Agric. Food Res. Volume 21, article id 101975. https://doi.org/10.1016/j.jafr.2025.101975.