Green Energy and Technology

Allana Katiussya Silva Pereira
Ananias Francisco Dias Júnior *Editors*

Impacts of Using Biomass as an Energy Source in Homes

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Green Energy and Technology

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Energy Sources Used in Food Preparation and Impacts on Climate Change

Iara Nobre Carmona, Marina Passos de Souza, Elias Costa de Souza,
Kamilla Crysllayne Alves da Silva, Allana Katiussya Silva Pereira,
and Ananias Francisco Dias Júnior

Abstract One-third of the world's population does not have access to clean energy sources for food preparation. The use of inefficient technologies can increase the emission of potential greenhouse gases (GHG) and accelerate climate change. Recently, the increase in the price of Liquefied Petroleum Gas (LPG) caused by the COVID-19 pandemic made it possible to increase the use of firewood in the domestic environment, directly impacting people's health and the environment. In this context, the application of greener technologies can mitigate the harmful effects caused on people and nature. Thus, this chapter presents a description of the main primary sources of energy used in food around the world, specifically forest biomass and LPG, in addition to presenting the historical context that encompasses both energy sources. What were the main sources of energy used in the past? What has changed from the Neanderthal period to today? How was the use of Liquefied Petroleum Gas (LPG)

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and how is it today? How was the world scenario of firewood use in domestic environments and how is it currently? And other biomasses, did they already have space? How did the COVID-19 pandemic affect the use of these energy sources (forestry biomass and LPG)? What impacts do these energy sources have on climate change? What do the COP27 discussions bring as prospects? These were the questions that guided this chapter.

Keywords Forest biomass · Energy sources · Climate changes · Fuels · Food cooking

1 Introduction

There are several sources of energy used in food preparation, from fossil fuels to renewable energy sources. Each of these sources has a different impact on climate change, either through the emission of greenhouse gases or the way they are produced. One of the most common sources of energy in food preparation is cooking gas, which is a fossil fuel derived from petroleum. The burning of cooking gas emits carbon dioxide (CO_2) into the atmosphere, contributing to the increase in the greenhouse effect and consequently to climate change.

In addition to cooking gas, electricity is also a widely used source of energy in food preparation. Most of the world's electricity is produced from fossil fuels such as coal, oil, and natural gas. The burning of these fuels emits large amounts of CO_2 into the atmosphere, increasing the greenhouse effect and contributing to climate change.

However, there are also renewable energy sources that can be used in food preparation, such as solar energy and wind energy. Solar energy can be used to heat water or to generate electricity through solar panels. Wind energy can be used to generate electricity through wind turbines. These renewable energy sources are cleaner and do not emit greenhouse gases into the atmosphere.

In summary, the energy sources used in food preparation significantly impact climate change. It is important to opt for renewable energy sources and choose sustainably produced food to reduce greenhouse gas emissions and mitigate the impacts of climate change.

2 Main Energy Sources Used in the World: Historical Context

What makes humans unique? Why and how have humans become different from other animals in how they relate to their environments and each other? The distinction of humans as a species has been the subject of study by philosophers and scientists for as long as we have historical records. Richard Wrangham, an accomplished anthropologist, has written books presenting a new theory about how and why the human lineage (a group of primates known as hominids) evolved characteristics that distinguish us from other animals. In the book “Catching Fire: How Cooking Made Us Human”, [1] argues that the discovery of fire and cooking freed our human ancestors once and for all from an arboreal existence and led to a patriarchal social system and a division of work by gender. The main features that are the focus of this theory—technology, in the way fire is used and controlled—have long been heralded as features that make humans unique. His work builds on existing theories but goes a step further by incorporating new perspectives, trying to frame comprehensive and unified explanations for a set of human characteristics.

In “Catching Fire”, [1] focuses on cooking as an innovation that allowed the evolution of big brains. Early members of the Neanderthal lineage that led to modern humans (species within the genus *Homo*) discovered fire’s functions for cooking, warmth, and security, and eventually learned to manage and produce it [1]. With fire, humans no longer needed to sleep in trees as protection against predators and could transition to a completely terrestrial existence. With fire for cooking, many foods (such as tubers and meat) become softer, less toxic, and easier to digest. Humans have become physically and physiologically adapted to eating cooked food. Changes in the gastrointestinal tract allowed the evolution of early hominin bodies. This enabled them to allocate more resources to energy-intensive brain growth and maintenance. Reference [1] argues that adaptations found since *Homo erectus*—a species of modern human ancestor that appeared shortly after 2 million years ago—reflect this shift towards the use of cooked foods. Reference [1] also attributes to cooking the connection of male–female pairs (monogamy) and the gender division of labor in humans. He says that cooked food is a localized resource of high quality, and Neanderthals did it better. A male hominid was supposed to protect a female from aggressive attempts to steal her food. On the other hand, a male needed a female to cook for him because male hunting activities were time-consuming (Fig. 1) and, once hominids adapted to cooked food, it became impossible to efficiently process and digest raw food enough for survival [2].

Reference [1] also presents data from scientific research on nutrition and digestive processes, as well as more eclectic particulars of human survival on different diets (for example, the tribulations of raw food eaters), demonstrating that processed and cooked foods are easier to digest than raw food. Once the food is prepared and heated, energy (calories) can be more efficiently and completely extracted. Furthermore, there has been a substantial study on the anatomy of the gastrointestinal tract, linking the size and structure of certain organs to different types of [3]. Thus, the argument that consuming cooked food would allow for smaller gastrointestinal organs (which humans have relative to other animals of similar size) and provide more energy for the growth of a larger brain can be sustained. But there is still not enough evidence about fire control before the last few hundred thousand years to support Wrangham’s timeline, which would allow certain hominid adaptations to be reliably credited to cooking.

But how to get energy? What has changed from the Neanderthal period to today? Over the centuries, the way to generate energy has evolved a lot. The use of food as a source of energy has always been natural to human beings, but acquiring this resource has not always been easy. And because of that, they merely served to fulfil basic survival requirements and needs. Thus, the first advance in energy generation

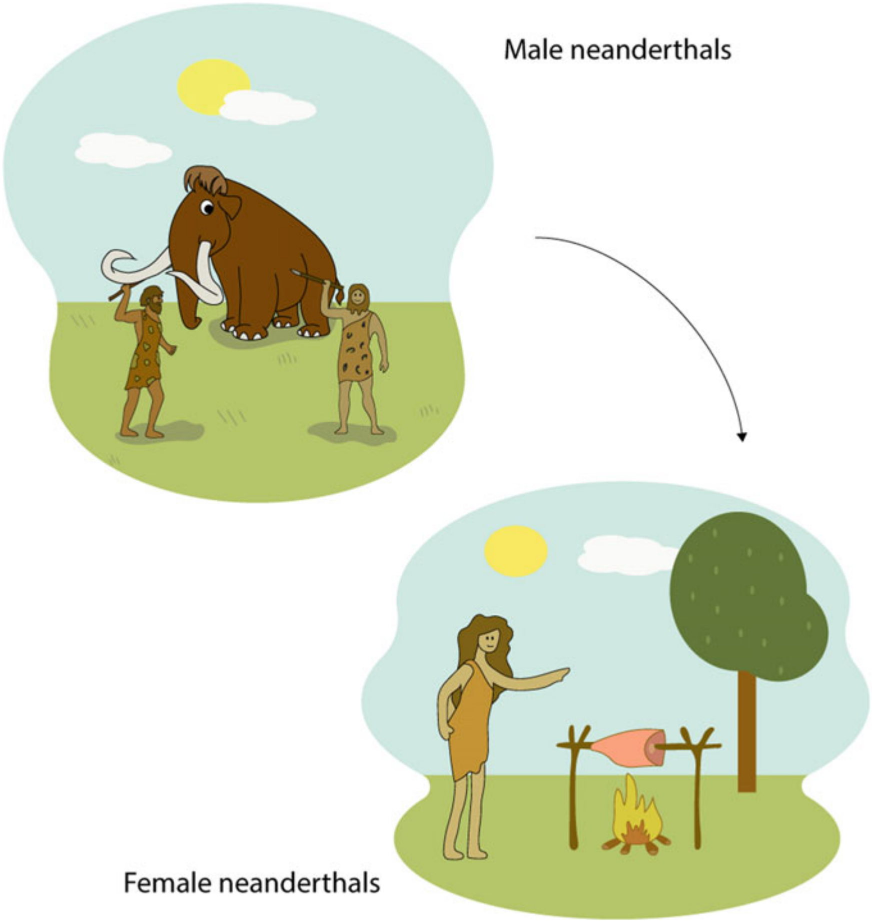

Fig. 1 Neanderthal division of labor according to sex (*Source* The authors 2023)

brought men a world of new possibilities. The discovery of fire made humanity aware of the benefits of heat, a resource that currently generally comes from the burning of fossil fuels, but which in the past, according to historical studies, happened through the use of firewood (biomass).

Around 500,000 years ago, during the Pleistocene, Europe's climate changed drastically, producing very different fauna and vegetation in glacial and interglacial periods [4]. More than 400,000 years ago, for example, in the interglacial periods, the exploitable plant and animal biomass was enormous, but it was mainly found in closed forests, dangerous and difficult to access. The Neanderthals (human groups at the time) exploited plant resources more than they did in the glacial periods, but practiced harvesting in clearings and, mainly, on the banks of rivers. In general, harvesting and hunting were enough for their survival and allowed them to grow, extend over a wider territory and even colonize a part of Asia.

Some archaeological evidence provides information about diets and landscape use. The use of fire, indicated by the presence of bonfires in many of the sites studied by archaeologists in the central and southeastern Iberian Mediterranean, was common and widespread in this period [3]. Furthermore, there is evidence of the use of fire in the Cueva Negra del Estrecho del Río Quipar spanning more than 780 km, with a rich paleontological and paleopalynological record demonstrating hot and humid environmental conditions, suggesting that the use of fire has a long history in this area.

As we have seen so far, the history of biomass and fire goes back to the roots of humanity. Biomass predates us. There is much evidence to support claims that we used biomass as an energy source between 230,000 and 1.5 million years ago (Cablevey [5]). Biomass is among the sources of renewable energy, that is, inexhaustible, whose production is part of the planet's carbon cycle, being a fuel used all over the world, and used to generate heat and cook food. From there, humans developed a fascination with what came to be known as bioenergy. Combustion was and remains the main way of converting biomass into energy. That is why biomass is still massively used in developing countries that do not have the bioenergy generation systems that more developed countries use to create alternative energy.

Humanity initially focused on using biomass for cooking and heating. Around the nineteenth century, we started to look for more modern uses of biomass materials. While fire is the oldest example of bioenergy in use, ethanol can be seen as the next big step in using carbon for energy. Ethanol has been around for a long time. Mankind discovered and used the fermentation process long before the development of civilizations. Despite this, there is no clear evidence of people distilling alcohol until twelfth century Italy [6]. Soon after people started making alcohol in the 1100s, ethanol was quickly used for cooking and lighting. People started using ethanol to create more energy. Ethanol was a very popular renewable energy source due to its simplicity and availability. It was derived from grains, which meant that the raw material was plentiful and all it took was a still to produce ethanol. It was until the substance, along with turpentine, was used to power the first engine in 1826. Ethanol fuel continued to be a popular form of fuel well into the 1890s.

As people began to explore the possibilities of ethanol as an alternative energy source, they also began to use vegetable and fish oil for heating and lighting [7]. Many civilizations used oils to generate heat and light. It is believed that even ancient cultures such as the Egyptians and Sumerians burned animal and vegetable oils. These oils were also used later in history. As populations grew, a new industry around lighting and heating emerged. People became more innovative and used the resources around them to produce light and energy. Examples include refined pine turpentine, alcohols (especially wood alcohol—methanol), and a mixture of the two, the main fuel before petroleum [8, 9].

Pine sap was a scarce renewable resource from the 1700s to the 1960s. Before oil, pine sap was a resource for which nations competed. In its raw form, pine sap was used in shipbuilding [10]. When distilled, the sap produced several chemicals that were extremely valuable at the time—the most important of which was turpentine. Turpentine has had multiple uses, but its most important use as an alternative energy source has been as lamp oil [11].

While it may seem like oil has been around forever, it was only refined and first used about 150 years ago [12]. Just like ethanol and turpentine, the energy demand has brought about a significant development in oil production. It's important to remember that oil wasn't useful until we figured out how to refine it into pieces. Various steam and internal combustion engines ran on a wide range of refined fuels. Rudolf Diesel beat them all when he created the diesel engine (Patricio Moreno [13].

An important milestone in the history of bioenergy was the beginning of the twentieth century when biomass fuel became popular again. Due to the "boom" of the automobile industry and wars, the automobile industry's lack of resources led to a return to bioenergy. Henry Ford is the most famous example of this, who switched to liquid biofuels and ethanol to power his vehicles. This became especially prevalent during World War I when fossil fuels became scarce [14]. The adversities and challenges of the time created a significant demand for ethanol.

The emerging renewable energy projects at the time had great potential. However, large-scale commercialization and mining have placed coal and oil at the forefront of the energy landscape [15]. They saturated the market and drove prices down. Furthermore, these non-renewable fuels have proven to be very efficient and practical for everyday use. This has brought a reduction in the use of bioenergy and an increase in fossil fuels. Fossil fuels became the fuel of choice in most countries and held the top position in energy consumption until the 1970s.

The geopolitical conflict that was felt in the 1970s created a fuel crisis [16]. As a result, the Organization of Petroleum Exporting Countries (OPEC) reduced oil exports. This caught the attention of governments and the academic world. Many began to look for other sources of renewable energy. This movement brought many improvements in green energy in solar panels, geothermal power plants, offshore wind farms, and hydroelectric power plants. During this period, scientists took a systematic approach to energy and coined the term biomass. Over time, the importance of bioenergy has been linked to issues such as fossil fuel pollution [17]. This period of biomass history is marked by some growing environmental concerns. Scientists have turned their attention to research on climate change and fossil fuel reduction.

Modern energy production from biomass is a vital source of renewable energy today. It has gone far beyond wind and solar energy in the quest for renewable energies. Biomass is the main source of renewable and alternative energy [18]. Biomass feedstock is processed and converted into energy in different ways. While the burning of woody biomass (forestry biomass materials, wood pellets, etc.) is an old process, innovation has brought us mass-produced energy crops converted to biofuel and biogas, and landfills that use anaerobic digestion to convert biomass into biogas for daily use.

Governments around the world have embraced the green movement and are implementing measures and protocols to raise awareness and ensure that much more green energy is produced. As we move forward, the field of biomass renewable energy technology is expected to grow. Biomass is expected to play a vital role in future energy-efficient power generation. Whether producing electricity, heat, or fuel for transport, its carbon neutrality hides many potentials. Renewable energy, whether in the form of solar, geothermal, hydroelectric, wind, or biomass, is here to stay. Biomass is an important source of renewable energy in the modern world. As biorefineries, processing plants, and businesses become more viable and popular energy solutions, they must have systems in place to ensure proper handling and production.

3 Use of Liquefied Petroleum Gas (LPG): An Overview

Liquefied Petroleum Gas (LPG), also known as autogas, is primarily composed of propane, butane, and isobutane in a variety of blends. The percentage of propane and butane in an LPG gas mixture ranges from 100% propane to 20% propane and 80% butane [19]. Small concentrations of other hydrocarbons may also be present. Depending on the source of the LPG and how it was produced, components other than hydrocarbons may also be present. It is a co-product of refining crude oil and processing natural gas. Its constituents are found in gaseous form at 20 °C and 1-atmosphere pressure (NTP) [20].

It is generally said that gaseous fuels emerged in the troubled times of World War II when gasoline shortages were common [15]. Interestingly and perhaps surprisingly, LPG was first used as a motor fuel long before the outbreak of war. The first mention of mixing propane and butane dates back to 1910 [21]. It was then that Walter O. Snelling, an American chemist who was researching the properties of gasoline, separated the gaseous fractions from the liquid ones, thus discovering the existence of propane. Two years later, in 1912, he started his first domestic propane installation, and in 1913 he patented its industrial-scale production. Later that year, the patent was purchased by Frank Philips, the founder of the oil company ConocoPhillips [22]. Even so, LPG consumption has not grown considerably.

Information on the practical use of LPG dates back to 1918 when the fuel was used for brazing lamps and metal cutting torches. However, commercial production did not begin until the 1920s. In 1928, LPG was used for the first time as an engine fuel (in a truck) and the first LPG refrigerator was manufactured [23]. In 1929, fuel sales reached 10 million gallons in the United States. LPG was rapidly gaining momentum. In the following years, the demand for Liquefied Petroleum Gas was further driven by the popularity of “airships”, traveling regularly between Europe and the US [24].

The then state-of-the-art Zeppelin series dirigible balloons were powered by engines fed with the so-called Blau gas (invented by Herman Blau), very similar to butane—one of the ingredients of LPG. The use of gaseous fuel with approximately the same mass as the air was very convenient for balloons, as it did not change the total weight of a Zeppelin in the same way as liquid fuels (blimps would become considerably lighter when liquid fuels were burned, thus forcing the release of hydrogen, which was extremely dangerous) [24]. However, when the Hindenburg—the largest airship ever built—was destroyed in a disaster in 1937, killing 36 people, the era of the Zeppelin ended abruptly.

However, the LPG era did not end with the Zeppelin era. On the contrary, it flourished, because there were a large number of gas canisters left at the airfields from which airships operated. In the state of Rio de Janeiro, Brazil alone, 6,000 gas cylinders became useless, which led businessman Ernesto Igel to have the idea of buying them and promoting gas as an excellent fuel for cooking food. This is how the Brazilian company, later known as Ultragaz, emerged [25]. In 1939, the company had three distribution trucks and 166 customers [26]. Eleven years later, in 1950, there were more than 70,000 customers and today Ultragaz is one of the largest LPG operators in the world.

When World War II ended and industrial production resumed growth, LPG sales in the US surpassed 1 billion gallons [27]. Nearly 62% of all US homes had LPG installations at the time. In 1947, the first liquefied gas tanker was built and entered service. In 1950, the Chicago Transit Authority, a public transportation operator in Chicago, ordered 1000 buses powered by LPG, while in Milwaukee 270 cabs were converted in the same year [28]. In 1958, LPG sales reached 7 billion gallons, and in 1965 Chevrolet introduced 4 new LPG engines for commercial vehicles. Initial international export contracts were not made until the 1950s. However, the amount of LPG exported was still low in the 1960s—less than 1 million tons were shipped out of the US [29]. Over the next 20 years, exports grew to 17 million tons and reached 48 million tons in the year 2000.

Currently, LPG is recovered from "wet" natural gas (gas with condensable compounds of heavy petroleum) by absorption [30]. The recovered product has a low boiling point and must be distilled to remove lighter fractions. It must then be treated to remove hydrogen sulfide, carbon dioxide, and water. The finished product is transported by pipelines and by specially built sea-going tankers. LPG reaches the domestic consumer in cylinders with relatively low pressure. Most of the LPG produced is used in central heating systems (a system that provides heat for an entire building), and the second largest as raw material for chemical industries. LPG is commonly used as a fuel for gas grills and gas stoves and ovens, gas fireplaces, and portable heaters [28]. In Europe, LPG water heaters are common. It is also used as engine fuel and for backup generators. Unlike diesel, LPG can be stored almost indefinitely without degradation.

LPG is used for cooking in many countries for economic reasons, convenience, or because it is the preferred fuel source. In India, approximately 8.9 million tonnes of LPG were consumed in the domestic sector in the six months between April and September 2016, mainly for cooking [31]. The number of domestic connections is 215 million (that is, one connection for every six people) with a circulation of more than 350 million LPG cylinders [32]. Most of the need for LPG is imported. Piped gas supply in India is not yet developed on a large scale. LPG is subsidized by the Indian government for domestic users. A rise in LPG prices has been a politically sensitive issue in India as it potentially affects the voting pattern of the middle class.

Aside from electric, induction, or infrared stoves, LPG stoves are the only type of fuel available in most suburban villages and many public housing developments. In Brazil, LPG is the most common cooking fuel in urban areas, being used in virtually all households, except the cities of Rio de Janeiro and São Paulo, which have gas pipeline infrastructure [33]. Since 2001, needy families have received a government subsidy ("Vale Gás") used exclusively for the purchase of LPG [34], and, since 2003, this subsidy has been part of the government's main social welfare program ("Bolsa Família"). Also, since 2005, the national oil company Petrobras differentiates LPG destined for cooking from LPG destined for other uses, establishing a lower price for the former. This is the result of a directive from the Brazilian federal government, but its discontinuation is currently being debated.

Currently, commercially available LPG is mainly derived from fossil fuels. Burning LPG releases carbon dioxide, a greenhouse gas. The reaction also produces some carbon monoxide. LPG, however, releases less carbon dioxide (CO_2) per unit of energy than mineral coal or oil, but more than natural gas. It emits 81% of the CO2 per kWh produced by oil, 70% by mineral coal, and less than 50% by coal-generated electricity distributed by the grid [35]. Being a mixture of propane and butane, LPG emits less carbon per joule than butane, but more carbon per joule than propane.

4 Modern Biomass and Traditional Biomass: Which Ones Grew the Most Around the World?

Despite biomass being widely used as a source of energy over the years, its use has been modernized through studies that have allowed technological implementations. In addition to the various improvements in burning systems, what we call modern biomass is opposed to traditional biomass in aspects related to how it is obtained. The biomass that was traditionally used was obtained in an extractive way, that is, the natural forests were exploited without the slightest planning and indications about the management and reestablishment of the species in the place. These extractive practices still exist today, especially in more economically affected communities [36]. However, with the modernization of knowledge about silviculture and sustainable forest management, countries like Brazil have been standing out for their innovative role in the rational use of forest resources and their correct application in the area of bioenergy [37].

Energy forests, as plantations with fast-growing species, good biomass productivity per area, and selected clones to maximize energy production are called, are already known by several segments of the bioenergy sector [37]. In addition to helping to reuse unproductive or poorly productive soils, these plantations help to fix carbon dioxide (CO_2) and contribute to reducing the use of non-renewable energy sources. These fast-growing species, mainly of the *Eucalyptus* genus, stand out for the energy quality generated from the thermochemical transformation processes, being considered of high quality both for direct burning (such as firewood) and for the production of charcoal [18, 37].

These advances in the more modern use of biomass also extend to the area of sustainable forest management, where recent studies point to the high potential of using the residues of these practices to produce energy in an environmentally friendly way [38]. These residues demonstrate that, when the material classification is performed correctly, energy gains can be maximized, which improves the energy quality of the material and ensures its correct use [39]. These studies are important, especially for more remote regions or those with difficult access to other energy sources, as is the case in the North region of Brazil, where the energy source available in greater quantity is biomass [38, 40]. However, due to several exploratory activities in the area, the use of forest residues has been proven to be a sustainable and viable alternative to meet the energy needs of these populations [40].

In addition to the already mentioned advances in the quality and obtaining of biomass, some transformations are being developed, related to the modification of the biomass form, more specifically working on the process of densification of this material [41]. The densification process is related to the reduction in the volume of biomass and, consequently, an increase in its density and the amount of energy concentrated per volume, i.e., higher energy density [42]. This densification process encompasses both briquettes and pellets and allows for a significant improvement in the energy quality of the biomass, as waste with a smaller granulometry is agglutinated and transformed into larger materials, which provides benefits for its transport, storage, and further use [42, 43].

Figure 2 illustrates the process of transforming the use of biomass (i) leaving the traditional form of extractive exploration of the native forest, (ii) moving to the planting of fast-growing species for wood production, and (iii) the most recent updates of densification biomass, transformation into pellets and briquettes that can be used in burning equipment in homes. This modernization process has been taking place over the years, gradually, where, currently, there are still countries that make use of "traditional biomass", with little technology. However, there are already several countries that have innovated in their technological aspects aimed at the energy area and already make use of "modern biomass".

The number of studies evaluating these new applications of biomass, or new materials, such as agroforestry residues, for energy applications, has grown significantly in recent years [44]. The maintenance and expansion of these studies are important to guarantee a continuous supply of modern biomass to different countries of the world. From the characterization of the biomass and studies that evaluate in detail the most efficient transformation processes, from the energy point of view, it is possible to obtain a quality fuel that can be widely used in homes, reducing the consumption of wood obtained through the extractive consumption [18, 38]. The choice of biomass to be used is a factor of significant importance for energy planning in countries. Currently, with the trend of carbonization of economies and with the focus on renewable and less polluting sources, the choice for options derived from

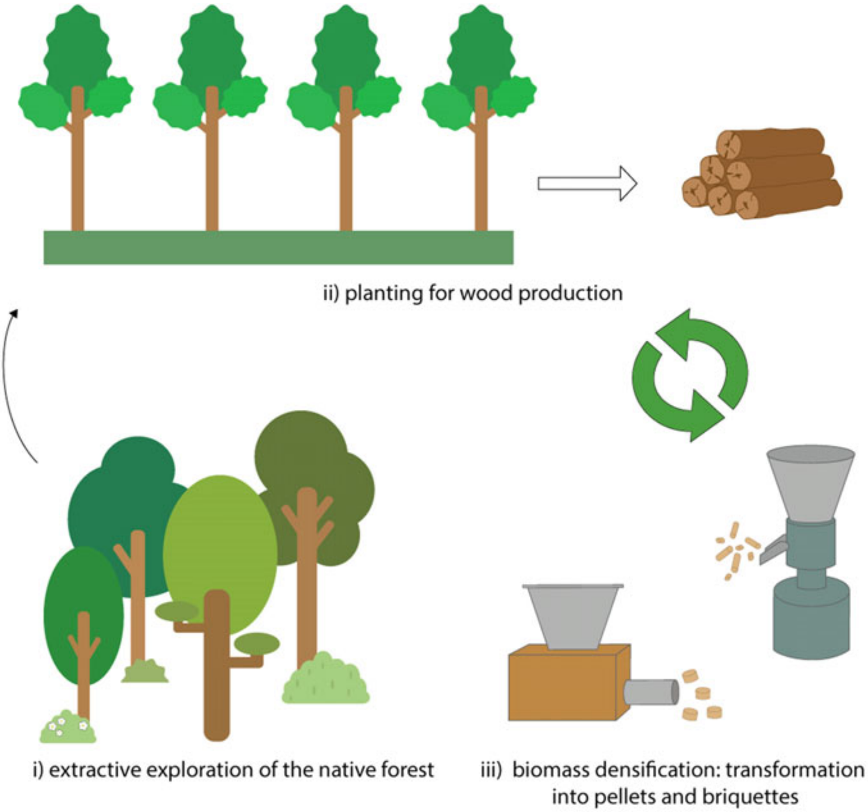

Fig. 2 The transition from "traditional" biomass to "modern" biomass (*Source* The authors 2023)

biomass becomes even more important, to the detriment of sources obtained from fossil fuels.

In addition, the insertion of these solid products produced from the densification of biomass in the market allows for an increase in the variability of renewable fuels available in markets in different countries of the world. With the correct study of lignocellulosic residues available in their respective countries or regions, technical feasibility studies can be carried out to assess the possibility of transforming these residues into solid fuels such as pellets or briquettes. Thus, two benefits are achieved directly: the first, which is the reuse of waste from a specific sector of that location; and the second is the availability of a cleaner energy source that contributes little to climate change, especially when compared to other non-renewable sources.

Even with these modernizations of biomass over the years, both in terms of fuel and in terms of burning equipment, in many parts of the world, Liquefied Petroleum Gas (LPG) has become the main energy source for cooking food in homes [45]. The impact generated on the air quality inside the homes that used firewood and started using stoves fuelled with LPG is undeniable, even knowing the environmental problems related to the exploitation of this fuel and the fact that it is not renewable [45]. This change in the energy source used in homes is related to technological advances and the implementation of different public policies in countries. In countries like Brazil, one of the important factors is socioeconomic, since, historically, firewood has been used by people in situations of social and economic fragility [45]. However, it is important to highlight that in addition to cultural and socioeconomic factors, some factors also seem to influence the choice of fuel to be used in homes. These factors are related to the price of LPG and proximity to the forest, given that much of the firewood used in homes is collected through extractivist [45].

Several studies correlate prolonged exposure to biomass smoke with the most diverse health problems, and this fact is observed for different extracts of the population, with studies indicating that children and women are the most affected, probably because they spend more time indoors [20, 46–48]. These health problems affect developing countries more significantly, where populations suffer from various economic problems [48]. Thus, it is necessary to invest more significantly in the modernization of equipment, as well as in strategies to modernize the biomass in these countries, avoiding the use of lower quality materials, and emphasizing investment in planting fast-growing species, to the detriment of unrestrained exploitation of its natural resources. Initiatives like the Clean Cooking Alliance [49] operate in different countries to provide more efficient equipment that uses biomass as fuel. However, several countries lack effective public policies to help these populations.

5 How Did the COVID-19 Pandemic Affect the Use of Forest Biomass and Liquefied Petroleum Gas (LPG) as an Energy Source?

The COVID-19 pandemic, decreed by the World Health Organization in March 2020, directly affected the lives of the entire world. Whether directly facing the health problems caused by the disease, including deaths, or the trail of economic destruction left by the impact of the paralysis of various productive sectors around the world [50]. These impacts on public health, economy, and culture of populations ended up generating several changes in habits that may, or may not, remain in these populations over the next few years. [51]. Among these changes, one of the main ones is linked to the daily lives of populations around the world: their diet.

In addition to wondering about the quantity and quality of food that will be eaten by their families, the people who are heads of these families are also concerned with issues related to the way their food is cooked, an activity present in different cultures around the world [52, 53]. The change in this traditional practice is directly related to the type of fuel used for cooking food. Due to financial needs, populations tend to migrate to cheaper and easily accessible energy sources. Avoiding, for example, dependence on the international price of oil, which can directly impact the price of LPG, and opting for available sources close to their homes, such as forest biomass.

This is a pattern that has been repeated over the years in several countries around the world, such as Brazil, a continental, diverse country with a high rate of social inequality.

Over the years, the consumption of the two main fuels used to cook food in Brazil (firewood and electricity) has varied according to the country's economic situation, which is a pattern throughout the world [54]. These economic factors are directly related to the quality, quantity and type of fuels used by communities to heat, light and, above all, cook in their homes [48]. Firewood, which was the main source of energy in homes, has been decreasing over the years, with LPG and electricity following opposite paths in this trend in Brazil.

From the 2000s onwards, with the implementation of public policies encouraging the use of electricity in homes and with the advancement of technologies, this change in the consumption behaviour of populations was even clearer, even with firewood showing a slight tendency to increase between the late 1990s to the end of the first decade of the 2000s. In recent years, with Brazil's political and financial crises, firewood consumption has grown again. This can be read as an indicator that this consumption may be related to the difficulty faced by families in purchasing LPG for cooking, even with government incentive programs, such as "Auxílio Gás" (gas aid), created by Law no. 14,237 of November 19, 2021 [55]. In addition, it is important to highlight that this data is formally collected and declared by consumers, that is, there is still much that is illegally exploited or consumed informally and not declared, given that a large part of the population that consumes firewood at home for financial reasons many times they do not buy firewood, but explore forests without quantitative control of actual consumption [45].

In addition to all the changes in the patterns of biomass consumption in homes over the years, due to different factors, the COVID-19 pandemic seems to have more significantly affected the substitution of fuels with a higher added value (LPG) for fuels with a lower added value (firewood). According to data from the National Energy Balance [54], firewood consumption in Brazilian homes increased from 7.2 to just over 7.44 million tons of oil equivalent (toe), between 2020 and 2021, an increase of 0 0.7% in the period, it is worth noting that the figures from before the pandemic (2019) showed an annual consumption of just over 7.08 million tons in households in the country. Meanwhile, the values that show the consumption of LPG, had a drop of 0.9% in the period between 2020 and 2021, going from 6.74 million toes to 6.52 million toes, with the pre-pandemic values, in 2019, in the house of 6.49 million toes.

This information is important to guide the decision-making of countries in a situation of economic weakness, as in addition to the economic factors of market fluctuations, exceptional events, such as the COVID-19 pandemic or the armed conflicts between Russia and Ukraine, end up further weakening the situation of these populations, which leads to an increase in the consumption of biomass for cooking food. Data from the National Energy Balance of Brazil demonstrate how this change in the pattern of energy consumption in homes was affected by the pandemic, however, we still do not have data on the impact of these changes in habits in the medium and long term [54]. Thus, it is important to follow up and monitor these families and carry out studies to assess the possible impact of this change on the economy and health of these people.

Often, because cooking is carried out in low-quality equipment, in addition to bringing health problems to its direct users, the smoke emitted during the combustion of biomass can significantly contribute to climate change and the decrease in air quality in different regions around the world [48]. However, it is also observed that the pandemic had a direct impact on the acceleration of the implementation of low-carbon energy sources in different countries, such as China, led mainly by the advance of solar energy and wind energy, which may have impacted the prospects of future carbon emissions in several countries [56]. Thus, the discussion of environmental issues at a global level becomes even more important, to highlight that, in addition to climate problems, health and food security problems are correlated in these situations.

6 Impacts of Forest Biomass and Liquefied Petroleum Gas (LPG) on Climate Change

Innumerable efforts are being made to use cooking fuels that are less harmful to the environment, to reduce indoor air pollution, improve air quality and reduce emissions into the atmosphere, as well as protect human health [57]. The assessment of impacts on climate change is mainly accounted for by the emission of greenhouse gases (GHG), mostly coming from fossil fuels. One of the fuel alternatives for cooking is Liquefied Petroleum Gas (LPG), which, despite being fossil, burns cleaner than other energy sources, such as mineral coal, and plays an important role in homes around the world, allowing more people to benefit from cleaner and more efficient energy, which 60% of the world's population already enjoys [30, 58].

Devices powered by LPG considerably reduce domestic air pollution when compared to rudimentary biomass burning, however, in many places there is still resistance to the use of these stoves, influenced by a combination of different socioeconomic, structural, and sociocultural factors, especially taste for food and preparation time. For these reasons, the implementation of the LPG, based stove in conjunction with the solid fuel stove can be an effective means of mitigating climate change and transacting the change in fuel type [28, 59, 60].

Another alternative to the use of GHG-emitting fuels is the use of forest biomass, which has a renewable character, in which carbon dioxide (CO_2) emissions can be reabsorbed in plant growth, through photosynthesis [61, 62]. Forest biomass has a high potential to be used in the transition from fossil fuels to bioenergy, however, its use faces some challenges related to the emission of GHG gases derived from fossil fuels. Mainly in the forest harvesting, processing, and transport processes and in the processing of biomass, which in addition to reducing the carbon sink area of forests, require inputs of materials and energy that emit GHGs [18, 62–64]. According to [65], it is necessary to adopt environmentally friendly forest management strategies to obtain forest products capable of impacting climate change mitigation. Active forest management, with high levels of harvest and efficient use of forest products, provides more climate benefits when in contrast to reducing the harvest and storing more carbon in the forest, acting in the mitigation of climate change [17].

It was generally assumed that CO_2 emissions derived from biomass had no influence on climate change, however, in the last decade, scientists have noticed that these emissions have a positive impact on climate change, with what is called the Global Warming Potential. Positive (GWPbio), during its stay in the atmosphere [2, 66, 67]. However, it is verified that the permanence of CO_2 emissions derived from biomass is shorter than those derived from fossil fuels, and is dependent on the biomass rotation time, due to the compensation effect of biomass growth to counterbalance the biogenic emission of CO_2, through photosynthesis [68–71].

If regeneration for compensation is accounted for to measure CO_2 emissions, it should be incorporated into Life Cycle Assessments (LCA—tool used to assess impacts [72]) of biomass use, as one of the positive impacts of bioenergy in mitigating climate change [73]. However, because the energy efficiency of bioenergy production based on forest biomass is low, it is necessary to have a greater amount of raw material available to produce this bioenergy, compared to the demand necessary to produce fossil fuels [62, 74]. Thus, if the GWPbio from forest biomass is included in the LCA, the impact of bioenergy on climate change can become twice as large as that of fossil fuels [75]. Despite this, studies such as the one carried out by [62], show that, although the balance of emissions generated by bioenergy (GHG derived from fossil fuels, biogenic CO_2 emissions, and regeneration for compensation) is positive and greater than the impacts of fossil fuels on climate change when integrating the negative impact generated by carbon sequestration and by stopping future carbon emissions from the equation, the final balance is reduced and much smaller than that of fossil fuels, ensuring that the use of biomass has total impacts favourable to the mitigation of climate change.

On the other hand, GHG emissions from biofuels present in their life cycle are still underestimated, since they exclude emissions due to land use or changes in land use practices. In this sense, the cultivation of energy crops and the collection of waste destined for bioenergy can increase unexpected GHG emissions, by altering the soil and, although the transition from agricultural land to energy crops has the potential to increase the content of organic matter in soil and improve its quality, this conversion faces difficult acceptance due to threats to food security [17, 76]. With this, the use of forest biomass creates a challenge for global climate policy: while fossil CO_2 emissions are partially avoided by the use of wood, other measures are needed to reduce the impacts generated by the reduction of the forest carbon sink and the changes in land use, as the goal is to reduce all GHG emissions in a few decades [65].

In addition to these obstacles, biomass burning is responsible for the release of other atmospheric pollutants, such as particulate matter (PM2.5), in which the particles that remain suspended in the atmosphere can interfere with the amount of solar radiation received by the Earth, through the dispersion and absorption processes, causing heating or cooling of the atmosphere, depending on the physical–chemical and optical properties of the particles [77, 78]. However, there are big differences in the emissions generated by the combustion of biomass, depending on which stove is used and how it is used. New, clean-burning stoves emit significantly lower amounts of local air pollutants than traditional stoves; and emissions resulting from incomplete combustion are strongly related to the way biomass is burned, with the frequency with which wood is placed in the stove and how much air is available for combustion, to which new stoves have greater control of the combustion process and the airflow [79].

7 Prospects for Fuels Arising from Discussions at COP27

During the 26th Conference of the Parties (COP), held in Glasgow—Scotland in 2021, world leaders agreed to accelerate their actions due to the alarming increase in global temperatures released by the Intergovernmental Panel on Climate Change (IPCC). However, arriving at the 27th COP, held in Sharm el Sheikh—Egypt, it was possible to see that this did not materialize, and the world went through countless consequences of climate change, such as floods in Pakistan, the dry season in the United States, hunger in Africa and heat waves in Europe [80].

COP27 brought some guidelines with the Adaptation Agenda of Sharm-El-Sheikh, seeking to be established as "the COP of implementation". The Agenda goes through some important points, aiming to protect more than 4 billion people from the growing climate consequences. These include (i) transitioning the world to sustainable and more climate-resilient agriculture, increasing production by 17% and reducing emissions by 21%, without expanding agricultural frontiers and improving livelihoods; (ii) the protection and restoration of 400 million ha of areas in a critical situation, both in terrestrial and freshwater ecosystems, supporting indigenous peoples and local communities and also, together with them, transforming 2 billion ha into a management area sustainable; (iii) the investment of 4 billion dollars in the protection of 15 million ha of mangroves, with a view to actions to protect all of them in the future; (iv) expanding access to clean cooking to 2,4 billion people and mobilizing up to USD 300 billion to adapt and encourage 2000 of the world's largest companies to integrate climate risk and develop climate change adaptation and mitigation action plans [82].

At least 230 million dollars were donated to the Adaptation Fund to help less developed countries to adapt to the new targets, as well as the creation of a specific fund for developing countries to deal with Loss and Damage caused by climate change. Based on the FAO report on the state of the world's forests, a Partnership between Forestry and Climate Leaders was launched, to implement the commitments established at COP26 and halt forest loss, biodiversity loss, as well as halt land degradation until 2030, including mobilization of financial support for indigenous peoples and local communities. COP27 also launched the Food and Agriculture for Sustainable Transformation (FAST) initiative to address climate impacts on both agriculture and food security.

COP27 also reaffirmed the Paris Agreement target of limiting global warming to 1.5 °C, but with data from the IPCC report presented at the event, commitments made by countries still increase GHG emissions by 10.6% by 2030, which could cause warming of up to 2.5 °C by the end of the century. To meet the Paris Agreement target, emissions should decrease by 43% by 2030, a scenario that is far from becoming a reality. With that, a work plan was launched, aiming to accelerate efforts and gradually reduce the use of energy from mineral coal and eliminate subsidies to fossil fuels [81]. In this context, the countries participating in COP27 will have a lot to change in their policies, from energy bases to human rights policies, as well as the distribution of subsidies. It will be a long road, which requires commitment, so there is still a habitable world to fight for.

8 Conclusions

Historically, for both humans and the animal world in general, the fundamental question about food and energy has been that, to survive, an individual must acquire at least as much food energy as is expended in basal metabolism, reproduction, and acquisition of food. In recent years, the main point of interaction between food, energy, and health has changed radically. Access to unprecedented levels of usable energy and non-renewable energy transformation practices are responsible for most of the man-made greenhouse gas emissions that are causing climate change. This change, in turn, poses major risks to the health of the population, including affecting food production and nutrition.

The use of forest-based biomass has the potential to contribute to the mitigation of climate change. However, although biomass can supply a significant part of primary energy demand with low or negative GHG emissions, these parallel targets are sensitive to uncertain economic, technical, and political futures. In addition to being an abundantly available and renewable source, forest biomass is used by different crops over the years in different countries around the world. Research that defines strategies aimed at mitigating gaseous emissions from this energy source is important to ensure compliance with climate goals in developed and developing countries, without the need to resort to more fossil fuels.

References

1. Wrangham R (2009) Catching fire: how cooking made us human—Richard Wrangham—Google Livros. Basic books. https://books.google.com.br/books?hl=pt-BR&lr=&id=ebEOupKz-rMC&oi=fnd&pg=PP10&dq=Catching+Fire.+How+Cooking+Made+Us+Human&ots=sXVs4_8MDW&sig=5oNICKZBgs-M4MNk9VnsDm9PWAw#v=onepage&q=CatchingFire. How Cooking Made Us Human&f=false. Accessed 4 Mar 2023

2. Yan Y (2018) Integrate carbon dynamic models in analyzing carbon sequestration impact of forest biomass harvest. Sci Total Environ 615:581–587. https://doi.org/10.1016/J.SCITOTENV.2017.09.326
3. Salazar-García DC, Power RC, Sanchis Serra A, Villaverde V, Walker MJ, Henry AG (2013) Neanderthal diets in central and southeastern Mediterranean Iberia. Quat Int 318:3–18. https://doi.org/10.1016/j.quaint.2013.06.007
4. Sørensen B (2009) Energy use by Eem Neanderthals. J Archaeol Sci 36(10):2201–2205. https://doi.org/10.1016/j.jas.2009.06.003
5. Cablevey News (2003) The history of biomass as a renewable energy source—Cablevey® Conveyors. https://cablevey.com/the-history-of-biomass-as-a-renewable-energy-source/. Accessed 19 Feb 2023
6. Jákl J (2021) Distilled beverages. Brill
7. Phuah E-T, Yap JW-L, Lau C-W, Lee Y-Y, Tang T-K (2022) Vegetable oils and animal fats: sources, properties and recovery 1–26. https://doi.org/10.1007/978-981-16-5113-7_1
8. Mansoori GA, Agyarko LB, Estevez LA, Fallahi B, Gladyshev G, Santos RG dos, Niaki S, Perišić O, Sillanpää M, Tumba K, Yen J (2021) Fuels of the future for renewable energy sources (Ammonia, Biofuels, Hydrogen). https://doi.org/10.48550/arxiv.2102.00439
9. Stafford W, De Lange W, Nahman A, Chunilall V, Lekha P, Andrew J, Johakimu J, Sithole B, Trotter D (2020) Forestry biorefineries. Renew. Energy 154:461–475. https://doi.org/10.1016/J.RENENE.2020.02.002
10. Carvalho C, Fonseca N, Vieira De Castro F (2008) Notas sobre a Tecnologia de Construção Naval nos Estaleiros Navais Portugueses do Século XVI
11. Hudaya T, Widjaja O, Rionardi A, Soerawidjaja TH (2016) Synthesis of biokerosene through electrochemical hydrogenation of terpene hydrocarbons from turpentine oil. J Eng Technol Sci 48(6):655. https://doi.org/10.5614/j.eng.technol.sci.2016.48.6.2
12. Gupta R, Wohar M (2017) Forecasting oil and stock returns with a Qual VAR using over 150 years off data. Energy Econ 62:181–186. https://doi.org/10.1016/J.ENECO.2017.01.001
13. Patricio Moreno Montalvo HI, Patricio Pineda Maigua DI, Alberto Santos Correa III L (2022) Evolución e historia de los motores diesel. Polo del Conoc 7(10):744–760. https://doi.org/10.23857/PC.V7I10.4754
14. Johnstone P, McLeish C (2020) World wars and the age of oil: exploring directionality in deep energy transitions. Energy Res Soc Sci 69:101732. https://doi.org/10.1016/J.ERSS.2020.101732
15. Fischer-Kowalski M, Rovenskaya E, Krausmann F, Pallua I, Mc Neill JR (2019) Energy transitions and social revolutions. Technol Forecast Soc Change 138:69–77. https://doi.org/10.1016/J.TECHFORE.2018.08.010
16. De Freitas H, Gil C, Da Amazônia G, Brasileiro M, Empreendimentos G (2021) O PENSAMENTO GEOPOLÍTICO DE GOLBERY DO COUTO E SILVA E OS POVOS TRADICIONAIS NA AMAZÔNIA: UMA RELAÇÃO TENSA. Rev Geopolítica Transfront 1(1):120–140
17. Gustavsson L, Haus S, Lundblad M, Lundström A, Ortiz CA, Sathre R, Le TN, Wikberg PE (2017) Climate change effects of forestry and substitution of carbon-intensive materials and fossil fuels. Renew Sustain Energy Rev 67:612–624. https://doi.org/10.1016/J.RSER.2016.09.056
18. Reid WV, Ali MK, Christopherl, Field B, Correspondence WV, Reid D, Packard L (2020) The future of bioenergy. Glob Chang Biol 26(1):274–286. https://doi.org/10.1111/GCB.14883
19. Lee I, Bae DJ, Lee WK, Yang CM, Cho SW, Nam J, Lee DY, Jang AR, Shin HS, Hwang JY, Hong S, Kim KS (2019) Rapid synthesis of graphene by chemical vapor deposition using liquefied petroleum gas as precursor. Carbon N Y 145:462–469. https://doi.org/10.1016/J.CARBON.2019.01.004
20. Mazumder S, Lee A, Dube B, Mehra D, Khaing P, Taneja S, Yan B, Chillrud SN, Bhandari N, D'Armiento JM (2019) A clean fuel cookstove is associated with improved lung function: effect modification by age and secondhand tobacco smoke exposure. Sci Rep 9(1):1–8. https://doi.org/10.1038/s41598-018-37887-8

21. Raslavičius L, Keršys A, Mockus S, Keršiene N, Starevičius M (2014) Liquefied petroleum gas (LPG) as a medium-term option in the transition to sustainable fels and transport. Renew Sustain Energy Rev 32:513–525. https://doi.org/10.1016/J.RSER.2014.01.052
22. Minadeo R (2022) FUSÕES E AQUISIÇÕES (F&A's) NA INDÚSTRIA PETROLÍFERA: UMA VISÃO PANORÂMICA. Rev Estud Debate 29(2):28–60. https://doi.org/10.22410/ISSN.1983-036X.V29I2A2022.2970
23. James RW, Missenden JF (1992) The use of propane in domestic refrigerators. Int J Refrig 15(2):95–100. https://doi.org/10.1016/0140-7007(92)90033-Q
24. Hunt JD, Byers E, Balogun AL, Leal Filho W, Colling AV, Nascimento A, Wada Y (2019) Using the jet stream for sustainable airship and balloon transportation of cargo and hydrogen. Energy Convers Manag X 3:100016. https://doi.org/10.1016/J.ECMX.2019.100016
25. Colomer M, Lyra M, Pires-Alves C, Delorme Prado LC (2020) The market of LPG (Liquefied petroleum gas) in Brazil: a brief structural, institutional-historical perspective. Entrep Hist 99(2):21–34. https://doi.org/10.3917/EH.099.0021
26. Baryshevaa A, Jevgenij E, Markova A, Sergejs S (2023) Liquefied petroleum gas: market overview and pricing models. Econophysica. https://econophysica.ru/researches/liquefied-petroleum-gas-market-overview-and-pricing-models/. Accessed 5 Mar 2023
27. Taneja S, Singh P, Sharma A, Singh G (2021) Use of alcohols and biofuels as automotive engine fuel 161–183. https://doi.org/10.1007/978-981-16-1256-5_10
28. Nuño Martínez N, Mäusezahl D, Hartinger SM (2020) A cultural perspective on cooking patterns, energy transfer programmes and determinants of liquefied petroleum gas use in the Andean Peru. Energy Sustain Dev 57:160–167. https://doi.org/10.1016/J.ESD.2020.06.007
29. Ou S, Lin Z, Manente V, Bouchard J, He X, Lu Z, Gan Y, Zhou Y, Przesmitzki S, De Castro Gomez DJ, Aburas N, Lilley W, Calendini PO (2022) Light-duty vehicle transportation policy and implication on greenhouse gas emissions. ACS Symp Ser 1412:21–81. https://doi.org/10.1021/BK-2022-1412.CH002
30. de Mello SB (2022) GLP: potencial de sobra para uma matriz energética mais limpa – Sindigás. Sindigás
31. Patnaik S, Jha S (2020) Caste, class and gender in determining access to energy: a critical review of LPG adoption in India. Energy Res Soc Sci 67:101530. https://doi.org/10.1016/J.ERSS.2020.101530
32. Mariselvam V, Dharshini MS (2021) IoT based level detection of gas for booking management using integrated sensor. Mater Today Proc 37(Part 2):789–792. https://doi.org/10.1016/J.MATPR.2020.05.825
33. Lucon O, Coelho ST, Goldemberg J (2004) LPG in Brazil: lessons and challenges. Energy Sustain Dev 8(3):82–90. https://doi.org/10.1016/S0973-0826(08)60470-6
34. Gioda A (2019) Residential fuelwood consumption in Brazil: environmental and social implications. Biomass Bioenerg 120:367–375. https://doi.org/10.1016/J.BIOMBIOE.2018.11.014
35. Gürbüz H, Şöhret Y, Akçay H (2019) Environmental and enviroeconomic assessment of an LPG fueled SI engine at partial load. J Environ Manage 241:631–636. https://doi.org/10.1016/J.JENVMAN.2019.02.113
36. WHO WHO (2018) Household air pollution and health
37. de Paula Protásio, Roque Lima MD, Scatolino MV, Silva AB, Rodrigues de Figueiredo IC, Gherardi Hein PR, Trugilho PF (2021) Charcoal productivity and quality parameters for reliable classification of Eucalyptus clones from Brazilian energy forests. Renew Energy 164:34–45. https://doi.org/10.1016/j.renene.2020.09.057
38. Lima MDR, Patrício EPS, Barros Junior U de O, Silva R de CC, Bufalino L, Numazawa S, Hein PRG, Protásio T de P (2021) Colorimetry as a criterion for segregation of logging wastes from sustainable forest management in the Brazilian Amazon for bioenergy. Renew Energy 163:792–806. https://doi.org/10.1016/j.renene.2020.08.078
39. de Paula Protásio, da Costa JS, Scatolino MV, Lima MDR, de Assis MR, da Silva MG, Bufalino L, Dias Junior AF, Trugilho PF (2022) Revealing the influence of chemical compounds on the pyrolysis of lignocellulosic wastes from the Amazonian production chains. Int J Environ Sci Technol 19(5):4491–4508. https://doi.org/10.1007/s13762-021-03416-w

40. Lima MDR, Simetti R, de Assis MR, Trugilho PF, Carneiro ACO, Bufalino L, Hein PRG, de Paula Protásio T (2020b) Charcoal of logging wastes from sustainable forest management for industrial and domestic uses in the Brazilian Amazonia. Biomass Bioenergy 142:105804. https://doi.org/10.1016/j.biombioe.2020.105804
41. Oliveira PRS, Trugilho PF, Oliveira TJP (2022) Briquettes of acai seeds: characterization of the biomass and influence of the parameters of production temperature and pressure in the physical-mechanical and energy quality. Environ Sci Pollut Res 29(6):8549–8558. https://doi.org/10.1007/s11356-021-15847-6
42. de Souza EC, Gomes JPS, Pimenta AS, de Azevedo TKB, Pereira AKS, Gomes RM, Brito JO, Dias Júnior AF (2022) Briquette production as a sustainable alternative for waste management in the tannin extraction industry. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-022-23490-y
43. Ferreira G, Brito TM, da Silva JGM, Minini D, Dias Júnior AF, Arantes MDC, Batista DC (2022) Wood waste pellets as an alternative for energy generation in the Amazon region. BioEnergy Res. https://doi.org/10.1007/s12155-022-10446-w
44. Azevedo SG, Santos M, Antón JR (2019) Supply chain of renewable energy: a bibliometric review approach. Biomass Bioenerg 126:70–83. https://doi.org/10.1016/j.biombioe.2019.04.022
45. Gioda A, Tonietto GB, de Leon AP (2019) Exposure to the use of firewood for cooking in Brazil and its relation with the health problems of the population. Cien Saude Colet 24(8):3079–3088. https://doi.org/10.1590/1413-81232018248.23492017
46. Gordon SB, Bruce NG, Grigg J, Hibberd PL, Kurmi OP, Lam K bong H, Mortimer K, Asante KP, Balakrishnan K, Balmes J, Bar-Zeev N, Bates MN, Breysse PN, Buist S, Chen Z, Havens D, Jack D, Jindal S, Kan H, Mehta S, Moschovis P, Naeher L, Patel A, Perez-Padilla R, Pope D, Rylance J, Semple S, Martin WJ (2014) Respiratory risks from household air pollution in low and middle income countries. Lancet Respir Med 2:823–860
47. Kaur-Sidhu M, Ravindra K, Mor S, John S, Aggarwal AN (2019) Respiratory Health status of rural women exposed to liquefied petroleum gas and solid biomass fuel emissions. Air, Soil Water Res 12:117862211987431. https://doi.org/10.1177/1178622119874314
48. WHO WHO (2017) Burning opportunity: clean household energy for health, sustainable development, and wellbeing of women and children. World Health Organization
49. Clean Cooking Alliance (2022) Clean Cooking Alliance
50. Mogaji E, Adekunle I, Aririguzoh S, Oginni A (2022) Dealing with impact of COVID-19 on transportation in a developing country: Insights and policy recommendations. Transp Policy 116:304–314. https://doi.org/10.1016/j.tranpol.2021.12.002
51. Wassler P, Talarico C (2021) Sociocultural impacts of COVID-19: a social representations perspective. Tour Manag Perspect 38:100813. https://doi.org/10.1016/j.tmp.2021.100813
52. Li H, Leng X, Hu J, Cao A, Guo L (2023) When cooking meets confucianism: Exploring the role of traditional culture in cooking energy poverty. Energy Res Soc Sci 97:102956. https://doi.org/10.1016/j.erss.2023.102956
53. Lindgren SA (2020) Clean cooking for all? A critical review of behavior, stakeholder engagement, and adoption for the global diffusion of improved cookstoves. Energy Res Soc Sci 68:101539. https://doi.org/10.1016/j.erss.2020.101539
54. Empresa de Pesquisa Energética (2022) Brazilian Energy Balance. Rio de Janeiro
55. Brasil (2021) LEI N^{o} 14.237, DE 19 DE NOVEMBRO DE 2021. Brazil
56. Li K, Qi S, Shi X (2022) The COVID-19 pandemic and energy transitions: evidence from low-carbon power generation in China. J Clean Prod 368:132994. https://doi.org/10.1016/j.jclepro.2022.132994
57. Oke DO, Fakinle BS, Sonibare JA, Akeredolu FA (2020) Evaluation of emission indices and air quality implications of liquefied petroleum gas burners. Heliyon 6(8):e04755. https://doi.org/10.1016/J.HELIYON.2020.E04755
58. Isihak S, Akpan U, Adeleye M (2012) Interventions for mitigating indoor-air pollution in Nigeria: a cost-benefit analysis. Int J Energy Sect Manag 6(3):417–429. https://doi.org/10.1108/17506221211259655/FULL/PDF

59. Hartinger SM, Lanata CF, Hattendorf J, Verastegui H, Gil AI, Wolf J, Mäusezahl D (2016) Improving household air, drinking water and hygiene in rural Peru: a community-randomized–controlled trial of an integrated environmental home-based intervention package to improve child health. Int J Epidemiol 45(6):2089–2099. https://doi.org/10.1093/IJE/DYW242
60. Jetter JJ, Kariher P (2009) Solid-fuel household cook stoves: characterization of performance and emissions. Biomass Bioenerg 33(2):294–305. https://doi.org/10.1016/J.BIOMBIOE.2008.05.014
61. Darda S, Papalas T, Zabaniotou A (2019) Biofuels journey in Europe: currently the way to low carbon economy sustainability is still a challenge. J Clean Prod 208:575–588. https://doi.org/10.1016/J.JCLEPRO.2018.10.147
62. Hao H, Dai L, Wang K, Xu J, Liu W (2021) An updated framework for climate change impact assessment of bioenergy and an application in poplar biomass. Appl Energy 299:117323. https://doi.org/10.1016/J.APENERGY.2021.117323
63. Guo J, Gong P, Brännlund R (2019) Impacts of increasing bioenergy production on timber harvest and carbon emissions. J For Econ 34(3–4):311–335. https://doi.org/10.1561/112.00000500
64. Jåstad EO, Bolkesjø TF, Trømborg E, Rørstad PK (2020) The role of woody biomass for reduction of fossil GHG emissions in the future North European energy sector. Appl Energy 274:115360. https://doi.org/10.1016/J.APENERGY.2020.115360
65. Soimakallio S, Saikku L, Valsta L, Pingoud K (2016) Climate change mitigation challenge for wood utilization—the case of Finland. https://doi.org/10.1021/ACS.EST.6B00122
66. Liu W, Zhang Z, Xie X, Yu Z, Von Gadow K, Xu J, Zhao S, Yang Y (2017) Analysis of the global warming potential of biogenic CO_2 emission in life cycle assessments. Sci Reports 71 7(1):1–8. https://doi.org/10.1038/srep39857
67. Patel M, Zhang X, Kumar A (2016) Techno-economic and life cycle assessment on lignocellulosic biomass thermochemical conversion technologies: a review. Renew Sustain Energy Rev 53:1486–1499. https://doi.org/10.1016/J.RSER.2015.09.070
68. Cherubini F, Strømman AH (2011) Life cycle assessment of bioenergy systems: state of the art and future challenges. Bioresour Technol 102(2):437–451. https://doi.org/10.1016/J.BIORTECH.2010.08.010
69. Guest G, Cherubini F, Strømman AH (2013) The role of forest residues in the accounting for the global warming potential of bioenergy. GCB Bioenergy 5(4):459–466. https://doi.org/10.1111/GCBB.12014
70. Liu W, Wang J, Debangsu Bhattacharyya C, Cafferty K, Shawn Grushecky M, Schuler J, Singh K, Spatari S (2015) Economic and environmental analyses of biomass utilization for bioenergy products in the Northeastern United States. ProQuest
71. Pelletier C, Rogaume Y, Dieckhoff L, Bardeau G, Pons MN, Dufour A (2019) Effect of combustion technology and biogenic CO_2 impact factor on global warming potential of wood-to-heat chains. Appl Energy 235:1381–1388. https://doi.org/10.1016/J.APENERGY.2018.11.060
72. Hunt RG, Franklin WE (1996) LCA—how it came about—personal reflections on the origin and the development of LCA in the USA. Int J Life Cycle Assess 1(1):4–7. https://doi.org/10.1007/BF02978624/METRICS
73. Liu W, Yu Z, Zhu Q, Zhou X, Peng C (2020) Assessment of biomass utilization potential of *Caragana korshinskii* and its effect on carbon sequestration on the Northern Shaanxi Loess Plateau China. L Degrad Dev 31(1):53–64. https://doi.org/10.1002/LDR.3425
74. Chaves AMB, do Vale AT, Melido RCN, Zoch VP (2013) CARACTERÍSTICAS ENERGÉTICAS DA MADEIRA E CARVÃO VEGETAL DE CLONES DE Eucalyptus spp. Biosf Enciclopédia Científico Conhecer-Goiânia, Cent 9
75. Liu W, Xu J, Xie X, Yan Y, Zhou X, Peng C (2020) A new integrated framework to estimate the climate change impacts of biomass utilization for biofuel in life cycle assessment. J Clean Prod 267:122061. https://doi.org/10.1016/J.JCLEPRO.2020.122061
76. Njakou Djomo S, Witters N, Van Dael M, Gabrielle B, Ceulemans R (2015) Impact of feedstock, land use change, and soil organic carbon on energy and greenhouse gas performance of biomass cogeneration technologies. Appl Energy 154:122–130. https://doi.org/10.1016/J.APENERGY.2015.04.097

77. Artaxo P, Rizzo L V, Paixão M, De Lucca S, Oliveira PH, Lara LL, Wiedemann KR, Andreae MO, Holben B, Schafer J, Correia AL, Pauliquevis TM (2009) Partículas de Aerossóis na Amazônia: Composição, Papel no Balanço de Radiação, Formação de Nuvem e Ciclos de Nutrientes. Glob Chang Geophys Monogr Ser 186. https://doi.org/10.1029/2008GM000778
78. Lima FDM, Pérez-Martínez PJ, de Fatima AM, Kumar P, de Miranda RM (2020) Characterization of particles emitted by pizzerias burning wood and briquettes: a case study at Sao Paulo, Brazil. Environ Sci Pollut Res 27(29):35875–35888. https://doi.org/10.1007/S11356-019-07508-6/METRICS
79. Solli C, Reenaas M, Strømman AH, Hertwich EG (2009) Life cycle assessment of wood-based heating in Norway. Int J Life Cycle Assess 14(6):517–528. https://doi.org/10.1007/S11367-009-0086-4/METRICS
80. Friedman L (2022) What is COP27 and what’s at stake? What to know about the UN’s climate summit. The New York Times. New York Times
81. Gurgel e Silva JP (2023) COP 27 e a participação brasileira|Politize! Politize
82. COP27 (2022) COP27—COP27 Presidency launches Sharm El-Sheikh Adaptation Agenda

Biomass as a Biofuel Used in Food Preparation: Qualitative Variables that Contribute to People's Quality of Air and Life

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Abstract The use of biomass for cooking food is a daily activity for many families and can cause an increase in morbidity and mortality in different parts of the world. Improper burning of this material can generate various polluting compounds that negatively impact the environment and people's health. Wood-burning stoves and fireplaces emit significant amounts of harmful pollutants, including several carcinogenic compounds, with CO and NO_x being two of the primary gaseous pollutants from wood smoke. Thus, the objective of this chapter was to discuss the main variables that contribute to people's air quality and life. For this, we debated biomass as a

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biofuel in food cooking, the combustion of biomass in air quality and people's health, the evolution of cooking methods, the use and effect of biomass use in domestic environments, and how to tackle the challenge of clean cooking. It was observed that the methods of preparing food with forest biomass are often carried out incorrectly, often with outdated preparation methods. This occurs mainly in developing countries by families without prior knowledge of the risks, or when there is knowledge, there need to be more economic subsidies.

Keywords Air pollution · Respiratory diseases · Biomass burning

1 Introduction

The dependence on biomass has had its origins since ancient times. Defined as any organic material derived from plants, animals, and waste that can be used as a source of energy, this material has an important place in the history of humanity [55]. Biomass was the first energy source that humans were able to control and use its energy [10]. When burned, this material releases energy through heat, which can be used for cooking or heating. Until two centuries ago, biomass was the world's primary source of energy [20]. Over the years, new sources of energy generation have developed, but biomass, along with kerosene, remains the main source of energy for cooking food for about 3 billion people worldwide. The proportion of the population that depends on biomass for cooking is higher in sub-Saharan Africa and India [74]. That's right, one-third of humanity primarily cooks with biomass [32]. For centuries, this material has been a part of society's daily life and continues to be used today. In various regions of the planet, biomass, such as wood, harvest waste, wet cake, or charcoal, is used for cooking food and heating and lighting residences.

Biomass is a traditional and widely used fuel for cooking food in many countries worldwide. Often related to cultural practices, biomass is considered a sustainable and eco-friendly option for cooking food, especially in rural areas. In countries such as India, China, Africa, Brazil, and Indonesia, biomass is considered the primary raw material for preparing food in rural areas [7, 49, 55, 56]). Cooking with biomass has traditionally been practiced in developing countries where other fuel sources are scarce [45]. However, we emphasize that there is a small portion of the population that uses biomass in a more "noble" way, in preparing food for people with higher purchasing power, such as in barbecues, pizzerias, and other dishes considered valuable by the fuel, such as the "dirty steak" made with food directly on charcoal embers.

One of the advantages of cooking food with biomass is that this raw material is considered a renewable energy source. Unlike fossil fuels, which are finite and non-renewable, biomass can be grown and harvested continuously [23]. This makes this cooking practice an eco-friendly option for cooking food. There is a range of methods for cooking food from biomass, from direct contact with the heat source to open and closed ovens that use pots and other utensils for boiling, cooking, and baking based on indirect contact with the heat source generated by the fuel [22, 63]. We emphasize that there are various possibilities for using biomass for cooking food. However, cooking with biomass has its challenges.

One of the main challenges is reducing smoke and other pollutants emitted during the cooking process, which can have adverse health effects [25, 46]. W To address this issue, several studies have been conducted worldwide, aiming to evaluate the impact of indoor air pollution caused by biomass burning on human health and seeking solutions to this situation. Effective solutions to reduce indoor air pollution require the development and implementation of policies and programs that promote the adoption of cleaner cooking technologies and fuels. Additionally, education and training to communities on the importance of indoor air quality and the risks associated with indoor air pollution are vital to achieve significant results. In this context, it is essential to consider qualitative variables of biomass that can influence air quality and, consequently, human health. This chapter aims to provide insights into the factors affecting biomass combustion and the resulting air pollution. By understanding the key factors influencing biomass combustion, policymakers, researchers, and communities can work together to develop and implement effective solutions to reduce indoor air pollution and improve human health. Overall, addressing the issue of indoor air pollution caused by burning biomass for cooking and heating purposes is crucial to achieving the Sustainable Development Goals and improving the health and well-being of people around the world.

2 Biomass Combustion X Air Quality

Despite biomass's numerous benefits, its use has become a concerning factor [98]. One of the main challenges is that biomass as fuel is subject to the release of smoke and other hazardous pollutants to human health and the environment, mainly related to the equipment used in combustion. When biomass is burned in traditional stoves or fires, it releases various harmful pollutant gases into the air. These combustion gases can contain particulate matter, nitrogen oxides (NO_x), sulfur oxides (SO_x), carbon monoxide (CO), volatile organic compounds (VOCs), and other pollutants (such as particulate matter) (Fig. 1) [36, 99].

NO_x can contribute to the formation of ground-level ozone and cause respiratory problems, while SO_x can cause respiratory and cardiovascular issues and contribute to acid rain [93, 100]. CO is considered a toxic gas that can reduce oxygen delivery to the human body and cause various health problems [57]. VOCs can contribute to the formation of ground-level ozone and other secondary pollutants [73]. Particulate matter (PM) is a mixture of solid and liquid particles suspended in the air that can negatively impact air quality and human health [18]. But why do these compounds form during biomass burning? The quantity and type of emissions produced by biomass combustion depend on several factors, such as the type and quality of biomass, the combustion technology used, and the operating conditions [2, 33].

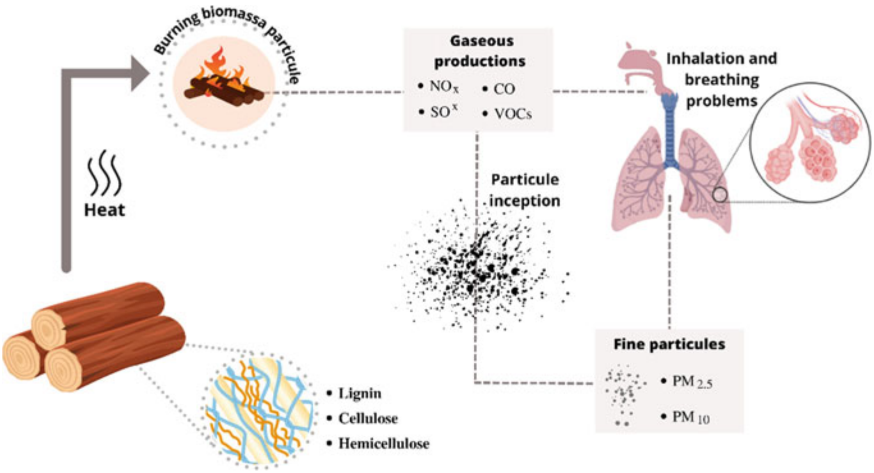

Fig. 1 Diagram of biomass conversion and gas release (*Source* The authors 2023)

A factor that can influence gas emissions during the combustion process of a solid fuel is its chemical composition. In general, the chemical composition of biomass fuels is less complex than solid fossil fuels [48]. Biomass is mainly composed of carbohydrates, such as cellulose, hemicellulose, and lignin, which are compounds of carbon, hydrogen, and oxygen [29, 83]. Although it has a chemical composition rich in carbon, oxygen, and hydrogen, many elements in its composition can be problematic during combustion, especially nitrogen (N) and sulfur (S), which can directly influence gas emissions [48]. Studies suggest that NO_x emissions from biomass combustion are directly related to the nitrogen content of the fuel [47, 61].

Regarding sulfur, the behavior of emissions is like that of nitrogen. The amount of SO_x emissions produced during combustion is related to the amount of sulfur in the biomass [13]. For example, some biomasses, such as agricultural residues, may contain higher levels of sulfur-containing compounds than others. Additionally, the presence of sulfur may depend on soil conditions and fertilizers used during biomass growth.

Another factor inherent to the characteristics of biomass that favors a greater amount of gas emissions during the combustion process is moisture. High moisture content limits thermal performance and increases pollutant emissions after slow or incomplete combustion [18, 54]. In addition to the intrinsic characteristics of biomass, how the material is combusted plays an essential role in gas emissions during its burning. For example, well-designed and operated combustion systems can produce more emissions than well-designed and operated systems [74]. When biomass is burned, incomplete combustion can occur due to a lack of oxygen, leading to the formation of carbon monoxide (CO) emissions [86]. In addition to the gases mentioned, volatile organic compounds (VOCs) are also a threat to air quality and may be related to both the biomass combustion process and the chemical characteristics of the material [65]. These emissions go far beyond air quality. Issues related to climate change and human health are among the main concerns that need to be considered regarding gas emissions from biomass burning.

3 Is Biomass a Problem for Human Health?

Cooking food is a necessary daily activity for human survival, but it can also pose health risks, especially when done with traditional equipment that relies on biomass fuels. Using biomass fuels, such as wood, crop residues, and animal dung, is common in many developing countries, particularly in rural areas where access to modern energy sources is limited. Although biomass fuel is an important energy source for millions of people, it also presents significant health risks, especially for women and children. The smoke and vapors released while cooking with biomass fuels contain harmful pollutants such as fine particulate matter, carbon monoxide, nitrogen oxides, and volatile organic compounds, which can have serious health consequences [4, 24]. Human health and gas emissions from biomass burning are closely interconnected, as exposure to these emissions can significantly impact the health of individuals, particularly those living nearby or in areas where biomass burning is common. Biomass burning is the combustion of organic matter, such as wood, crop residues, and animal waste, and is a significant source of air pollution in rural and urban areas [79]. Respiratory diseases are one of the primary health impacts of gas emissions from biomass burning [17, 39, 69].

Exposure to particulate matter, carbon monoxide, nitrogen oxides, sulfur dioxide, and other pollutants released during biomass burning can cause or exacerbate respiratory diseases such as asthma, chronic obstructive pulmonary disease (COPD), and bronchitis [27]. These pollutants can also increase the risk of lung cancer and other respiratory infections. In addition to respiratory diseases, biomass burning emissions can lead to cardiovascular diseases [34]. O Fine particulate matter released during biomass burning can penetrate deep into the lungs (Fig. 2) and enter the bloodstream, causing inflammation and increasing the risk of heart attacks and strokes [52, 87]. This particulate matter can also cause vasoconstriction, narrowing blood vessels and reducing blood flow to vital organs [52]. The most significant risk factors for these diseases are exposure to fine particles, carbon monoxide, and other harmful pollutants released during biomass burning. However, given a series of problems related to biomass use, the following question arises: is biomass really the villain?

4 Is Biomass Really the Villain?

Considering that the proper use of energy ensures the continuity of life and the sustainable development of communities, energy consumption management is one of the main topics on the agenda of all countries [1]. One of the energy sources in developing countries is biomass-based fuel [41]. This creates a conflicting factor:

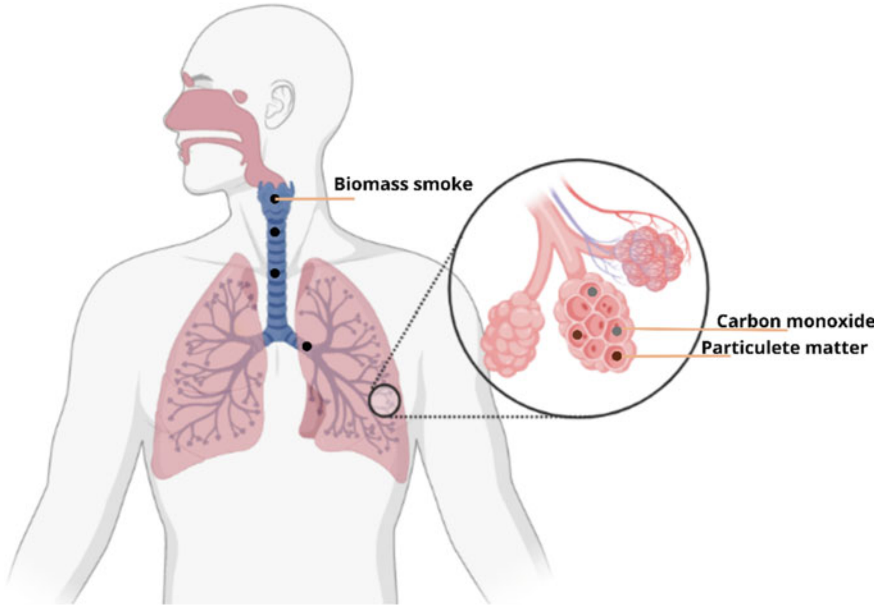

Fig. 2 Demonstration of the occurrence of cardiovascular diseases due to long-term exposure to smoke from burning biomass (*Source* The authors 2023)

the incidence of diseases due to high exposure to combustion compounds. Using biomass, especially wood, and charcoal, for cooking food is one of humanity's oldest and most widespread methods. Over time, the use of equipment to handle fire has become a common practice that has been perpetuated for generations. Even with technological advances in recent times, humans still face a series of challenges in the best way to use fire, using various types of stoves to facilitate food preparation [40]. One of the types of stoves used in developing countries is a wood stove. This type is used for cooking food and residential heating. However, these stoves need to present an ideal standard. Some lack chimneys; others have inefficient or poorly constructed chimneys, often subject to leaks in their operating system and ventilation methods [21].

In biomass-based stoves (popularly known as wood-burning stoves), the combustion of fuels often occurs incompletely, contributing to the generation of gases, fine particles, and compounds such as benzene, formaldehyde, and benzo[a]pyrene, which are highly carcinogenic to humans [21]. These components are also responsible for the growing incidence of respiratory infections, such as pneumonia, tuberculosis, chronic obstructive pulmonary disease, newborn malnutrition, cataracts, and even cardiovascular problems [3]. This is due to the need for more access to cooking and food preparation technologies, resulting from a confluence of factors ranging from the stove model to cooking in enclosed spaces. Almeida [5] analyzed the inefficiency of traditional wood-burning stoves and observed that their low-efficiency results in excessive and rapid firewood consumption due to incomplete energy utilization and faster fuel burning. In addition, the lack of insulation in the combustion chamber results in poor air circulation, leading to increased production and emission of toxic volatiles and soot particle [30]. These factors result in air pollution, leading to the health problems mentioned earlier.

The World Health Organization (WHO) has stated that approximately 2.4 billion people worldwide use wood and dung fires or stoves to prepare food (OMS 2022). This creates a problematic situation due to a combination of socio-environmental and economic factors, ranging from the stove model, the location of its use (in an open or closed area), and who operates it [59]. It is essential that biomass stoves meet the WHO Guidelines emission targets, as this is a determining factor in contributing to the health of those exposed to them daily.

5 Combustion with an Excess of Oxygen and Its Emissions

The biomass stove is a physical arrangement in which fuel is added in the presence of air, leading to the release of heat [28]. However, it is known that these devices are also characterized by low energy efficiency and high gas emissions. Air entry into the combustion chamber, either in the form of primary or secondary air, sustains the combustion process [74]. However, an excess of air can cause incomplete combustion and inadequate heat transfer due to reduced temperatures in the combustion chamber [88]. During this process of incomplete combustion of biomass, some toxic components are emitted, among them one of the main classes of organic pollutants, polycyclic aromatic hydrocarbons (PAHs) [64], black carbon (BC) [85], organic carbon (OC), carbon monoxide, nitrogen oxides (NO_x), sulfur dioxide (SO_2), ammonia (NH_3), benzene ($C_6 H_6$), formaldehyde (CH_2O) and others. Due to the low efficiency of combustion of these traditional stoves, large quantities of harmful effluents are produced to the environment and human health due to the incomplete burning of biomass fuel.

Biomass burning is a phenomenon capable of playing a fundamental role in terrestrial and atmospheric dynamics [60]. When a fuel particle is burned, a balance of ash fraction occurs due to simultaneous physical and chemical transformations, which are influenced by high temperatures [9]. The process of modifying the raw material and its constituent elements via heat in the presence of oxygen is called combustion [60]. Wood-burning stoves mostly do not have a mechanism for controlling the combustion process and require constant supervision by the operator. In many cases, they are operated improperly, contributing to incomplete combustion. This incomplete combustion results in the formation of gases such as carbon monoxide, breathable particulate matter, and a variety of greenhouse gases responsible for affecting human health and even contributing to climate change [70]. Another factor that affects the combustion process is the physical conditions of the biomass. In general, firewood for domestic burning does not follow a quality standard. Factors such as high moisture content, shape, size, density, and ash content can influence the combustion process. It is known that various uncontrollable factors are influential in the combustion process. Due to the harmful effects on the environment and human health, the development of new technologies to control the combustion process in traditional stoves and the possible reduction in the emission of these effluents has become relevant.

6 The Evolution of Ways of Cooking

The mastery of the stove begins with the discovery of the usability of fire and archaeological excavations in Chou Kutien, China [37]. Historically, it is known that using fire was responsible for our development as humans, mainly when related to meal preparation. Fire improved the ways of better utilizing the nutrients in food. This resulted in the evolution of the human organism, which stopped eating raw meals and began cooking them. Around half a million years ago, the mastery of fire popularized a scenario of differentiated nutritional habits, allowing for increased nutritional gain through processes that gradually improved throughout human evolution, such as baking, drying, and even storing. These techniques were responsible for allowing settlement and exploring the potential of plants. They even led to the improvement of different cooking methods, such as boiling stones in leather or wooden containers [12].

The cooking methodologies of prehistory evolved with the use of fire. Subsequently, they improved to other traditional and widely used methods, such as the “three-stone” “wood stove type,” which operates based on wood burning. In its arrangement, three large, undefined stones support pots and vessels over an open bottom (Fig. 3) [53]. The designs of three-stone or “trempe” stoves are as their name implies. Compared to open fires, these stoves are considered inefficient. They are remarkably similar in their functioning methodology, allowing a large part of the heat to dissipate and gradually waste its fuel (wood) [95]. Over time, these stoves have steadily improved. Using a mixture of mud, water, and animal waste and some changes in shape, the traditional oven passed from “three stones” to the “Chulha.” This improvement occurred exponentially, with the goal of better utilizing fuel-burning efficiency and indirectly minimizing emissions produced. Thanks to these adjustments, “modern” ovens could escape the smoke produced during biomass combustion outside of the kitchen in some stoves [50]. For example, the Chulha (fireplace in Hindi), traditionally used in India and other countries but not named, generally consists of a clay stove that operates based on biomass or humus-based fuels and is used for cooking meals (Fig. 3a) [43].

Fixed Chulhas with smoke removal apparatus is known as smokeless Chulhas and are modified versions of traditional Chulhas. As an example, the “Mid Chulha” does not have a smoke director and has a “U” shape. Reference [58] reiterated that Chulhas are designed for better fuel performance, promoting slightly more efficient combustion due to the presence of the chimney. Fuel consumption is reduced, and exhaust gases are removed through the chimney. The authors also considered that this cooking equipment has a 25–35% thermal efficiency and consumes less fuel. Another

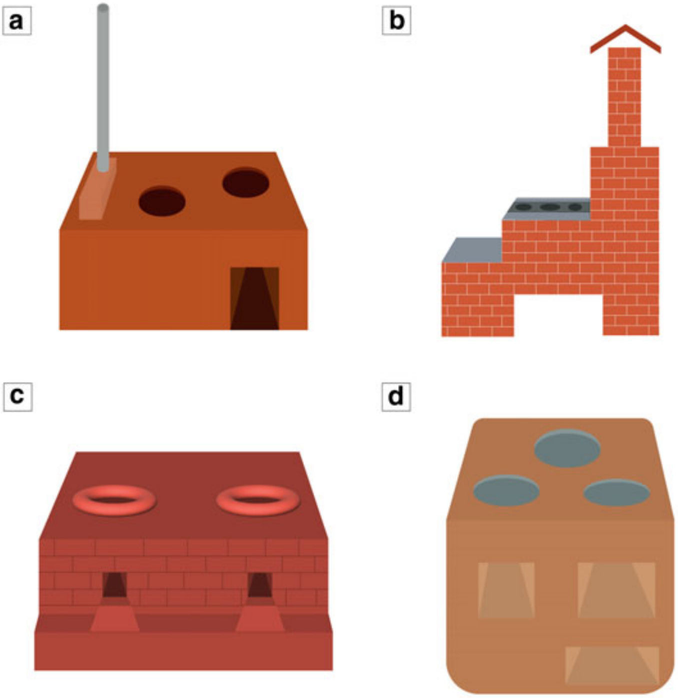

Fig. 3 Representation of stoves from different countries. Where: **a** Chulha stove; **b** traditional masonry stove; **c** Popular kiln in Kenya: Chepkube; **d** Traditional stove in Kenya: Cheproketes (*Source* The authors 2023)

traditional wood-burning stove model in Brazilian communities is made of masonry, cement, clay, and perforated metal plate for up to 5 pots (which may vary) (Fig. 3b). Some models of this oven already have a location for the exhaust gases to escape outside the residence (chimneys), but many still need this mechanism. Moreover, these wood-burning stoves have a low energy yield, emitting a considerable amount of gases and particulates inside the residences, harming the operator's health [40].

In other countries such as Kenya, besides the three-stone stove, which has become popular, different types of stoves are also used for cooking, such as the Chepkube stove (Fig. 3c) with a 30.8% adoption rate among the population and then the Cheprocket stove with 8.9% usability [42]. When compared to other stoves, it can be observed that the Chepkube stove has a more comprehensive air intake. The Chepkube stove is an improved stove that typically features a clay lining. This stove is considered improved due to its fuel efficiency and, thus, lower emissions [84]. However, Cheproketes stoves (Fig. 3d) have lower energy efficiency and promote higher CO exposures compared to the Chepkube stove. The percentage of incomplete combustion is worsened due to poor air circulation in the combustion chambers, where there is usually a buildup of ashes that causes blockage. Therefore, using different biomass stoves is based on the socioeconomic issues of the communities that use them. There are many adaptations of biomass stoves in different countries, but they all have the same functionality and operating principle. It is essential to understand that the wood-burning system's lack of standardization and acquisition can be harmful despite the stove being based on biomass. Even though biomass is a renewable energy source, these stoves favor incomplete combustion of the material, releasing polluting gases that affect human health, especially women and children, and exacerbate the climate crisis. It is known that traditional technologies can have a negative impact on health, providing chronic diseases and premature deaths, going beyond the energy issue, and causing recurring problems for one gender in particular: Women, who have daily responsibilities for household tasks [8]. Therefore, it is necessary to employ new technologies that are accessible for cooking, accessible to all, and enable clean and sustainable cooking.

7 Traditional Fuel: Inadequate Burning in Environments

Regarding air pollution, the first association is usually air pollution in large urban centers, with images of pollutants being emitted by vehicles or even companies. However, this scenario is not limited to these areas only; a considerable portion of the world's population lives with another source of pollution: burning forest biomass for domestic use (wood, charcoal, etc.). Approximately three billion people depend on traditional biomass for cooking and heating, causing various socio-environmental problems. About 35% of the population still used firewood for cooking in 2019, with 37% depending on Liquefied Petroleum Gas (LPG), natural gas, or biogas, and 10% on electricity [19]. The impact on health and the environment from using traditional fuels is significant—and affects women disproportionately, as they are primarily responsible for household chores. At least about 2.6 million people were without access to clean cooking in 2019, and slow progress predicts that by 2030—the target year to achieve the Sustainable Development Goal (SDG)—2.4 billion people will continue to use traditional fuel [19].

As seen in the data presented above, a large part of the population still uses traditional stoves (such as wood stoves) for cooking, using inefficient raw materials that often result in "inadequate burning," causing various health and environmental damages. The health risks associated with biomass burning in household environments have been linked to acute respiratory infections, chronic obstructive pulmonary disease (COPD), pneumoconiosis, pulmonary tuberculosis, and adverse effects during pregnancy. Such effects are more likely to occur in developing countries, where women and children are particularly vulnerable to the health impacts of indoor air pollution from cooking with biomass fuels [16, 26]. Women, in particular, often spend many hours a day cooking over open fires or traditional stoves, exposing them to high levels of smoke and other pollutants. Children are also at risk, as they spend a significant amount of time indoors and are more susceptible to respiratory infections due to the development of their immune system. Domestic air pollution is the fourth most important risk factor for the global disease burden and, according to reports, causes approximately 3.5 million premature deaths annually [33, 35]. Of these deaths, a large proportion is attributed to respiratory diseases, such as COPD, pneumonia, and lung cancer [31].

This type of domestic pollution affects the health of women who cook and children, who are especially susceptible to declining lung function, chronic bronchitis, and respiratory infections, and is the leading cause of death in children in developing countries [91, 92]. Reference [38] state that exposure to domestic pollution from biomass burning during the first trimester of pregnancy can contribute to lower fetal weight gain. The elements analyzed in the present research were ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), particulate matter with a diameter of less than 10 μm (PM10), and carbon monoxide (CO). The research demonstrated that 4.6% of newborns had a birth weight of less than 2500 g, which was statistically significant. Inadequate burning results in the formation of potentially toxic substances, such as carbon monoxide (CO), ammonia (NH_3), and methane (CH_4), among others, with fine particles containing particles smaller or equal to 10 μm (PM10), i.e., inhalable particles, being the most toxic pollutants that have been studied. Constituting the largest percentage (94%) of fine and ultrafine particles, these particles reach the deepest parts of the respiratory system, causing severe diseases [96, 99, 100].

8 Effect of Biomass Burning on Health

As the ability to control fire is often considered the distinguishing feature of prehuman evolution and wood is the oldest fuel, it is true that exposure to wood smoke is as old as humanity. Since domestic use dominates the total fuel demand in many developing countries, especially in rural areas, biomass will likely continue to be the primary energy source for a considerable portion of humanity. Per capita use is highly dependent on local conditions. Countries with abundant wood supply, such as Finland, Sweden, and Canada, burn more biomass fuels per capita than most other countries, while those with low supply, such as South Korea and Singapore, burn less [80–82].

The notion that wood smoke, being a natural substance, must be benign to human beings is sometimes still heard. It is well established, however, that wood stoves, fireplaces, and forest and agricultural fires emit significant amounts of health-harmful pollutants, including several carcinogenic compounds (e.g., polycyclic aromatic hydrocarbons, benzene, aldehydes, and respirable particles). Some of these toxic pollutants during biomass burning, according to researchers Naesher et al. (2007) and [6] were represented in Fig. 4.

CO and NO, two of the primary pollutants in wood smoke, add to atmospheric levels of these gases emitted by other combustion sources. The health effects of

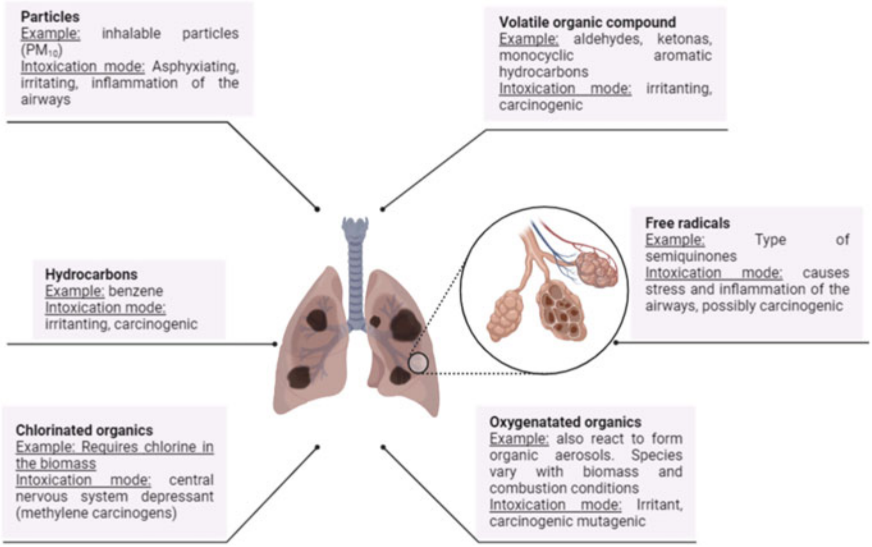

Fig. 4 Primary pollutants harmful to health from biomass combustion (*Source* The authors 2023)

exposure to these gases and other components of wood smoke (e.g., benzene) are well-known in the scientific community. Emissions from biomass burning contain a wide variety of solid, liquid, and gaseous constituents that can change rapidly over time, temperature, sunlight, and interaction with other pollutants [77, 78]. Several constituents are known to be hazardous to human health but are not specifically regulated or even thoroughly evaluated for their health effects. Wood-burning particles are typically smaller than 1 μm, with a peak in the size distribution between 0.15 and 0.4 μm. This is the case with other combustion mixtures, such as diesel fuel and tobacco smoke. In fact, most of the particle mass in old wood smoke is formed by such condensation processes. Fine particles in this size range (0.15 and 0.4 μm) efficiently escape the mucociliary defense system and are deposited in the peripheral airways, where they can exert toxic effects. Particles in this size range are not easily removed by gravitational settling and thus can be transported long distances [72, 75, 76].

The transport of biomass combustion particles over hundreds of kilometers has been extensively documented [22, 44]. Studies conducted by [44] show that modern stoves emit 95% fewer PAH16 and 13 fewer total suspended particles (TSP) than wood stoves. Many gaseous species are converted into other gases or particles during transport. The “black carbon” from biomass emissions are believed to contribute to regional and global climate change and adverse health effects in some parts of the world [66–68]. Methoxyphenols are a class of chemicals derived from the pyrolysis of lignin wood polymer. This class of chemicals covers a range of volatilities, from relatively volatile (e.g., guaiacol) to exclusively particle-associated. These chemicals are relatively abundant in wood smoke, although the most abundant compounds are predominantly in the vapor phase [96, 97, 99]. Accurate chemical analysis of methoxyphenols has proved to be an analytical challenge. Many methoxyphenols have been considered chemically reactive—a property that would impair their suitability as tracers for biomass smoke [15, 66]. Methoxyphenols have been used as tracers of wood smoke in multivariate source apportionment models to determine the proportion of urban fine PM derived from wood burning [11, 14].

9 Meeting the Challenge of Clean Cooking

Due to incomplete combustion and the lack of adequate air pollution control devices, emissions from burning biomass fuels contribute substantially to air pollution [90, 92, 94]. Various cultural, economic, and social factors directly influence the adoption of clean cooking solutions. However, some options are available to rapidly expand adoption in an environmentally sustainable manner and bring various co-benefits. Renewable alternatives such as improved biomass stoves, biogas, ethanol, and solar cookers already contribute to expanded access. Renewable energy-enabled electric cooking has also begun to play an important role [71, 85, 89]. Biogas-based solutions have been deployed for a long time to expand access to clean cooking and improve agricultural waste management.

However, inadequate policies banning traditional fuels and the high price of clean and renewable energy have weakened the motivation of households to use renewable energy. Meanwhile, low income and a lack of clear understanding of pollutants from burning biomass fuels have led families to adopt biomass fuels as a substitute for clean energy, which can further aggravate regional air pollution [51, 62]. Due to the current energy dilemma, a national cessation of biomass fuel burning and promoting an energy transition are incredibly challenging. Some measures that government agencies can take include reviewing and implementing national air quality standards in accordance with the latest WHO guidelines, monitoring air quality and identifying pollutant sources, and supporting and incentivizing the transition to exclusive use of clean domestic energy for cooking, lighting, and heating, and including air pollution themes for both domestic and urban centers in basic cycle disciplines, and providing tools for engagement in the health sector for citizens who do not have access to this knowledge.

10 Conclusions

The use of biomass as a fuel source can also generate harmful gas emissions, including carbon monoxide (CO), nitrogen oxides (NO_x), and volatile organic compounds (VOCs). These emissions can have detrimental effects on human health, such as respiratory and cardiovascular diseases, and contribute to air pollution, which is a significant public health concern worldwide. The amount and composition of gaseous emissions from biomass combustion depend on several factors, including the type of biomass used and characteristics of the biomass involved in the process, such as humidity, density, chemical composition, and even the presence of resin. Furthermore, inefficient combustion processes increase gaseous emissions. Various measures can be taken to mitigate the negative impacts of gas emissions from biomass combustion. These include using sustainable and low-emission biomass sources, improving combustion efficiency, implementing emission controls and monitoring systems, and promoting cleaner technologies such as gas stoves and ovens. Developing and adopting these measures can help minimize the negative impacts of biomass combustion and facilitate the sustainable and low-carbon use of this renewable energy source.

References

1. Abbaspour M, Karbassi A, Asadi MK, Moharamnejad N, Khadivi S, Moradi MA (2013) Energy demand model of the household sector and its application in developing metropolitan cities (case study: Tehran). Polish J Environ Stud 22(2):319–329
2. Adeniran JA, Yusuf RO, Abdulkadir MO, Yusuf M-NO, Abdulraheem KA, Adeoye BK, Sonibare JA, Du M (2020) Evaporation rates and pollutants emission from heated cooking oils and influencing factors. Environ Pollut 266:115169. https://doi.org/10.1016/j.envpol.2020.115169
3. Agrawal S, Yamamoto S (2015) Effect of Indoor air pollution from biomass and solid fuel combustion on symptoms of preeclampsia/eclampsia in Indian women. Indoor Air 25(3):341–352. https://doi.org/10.1111/ina.12144
4. Akteruzzaman M, Rahman MA, Rabbi FM, Asharof S, Rofi MM, Hasan MK, Muktadir Islam MA, Khan MAR, Rahman MM, Rahaman MH (2023) The impacts of cooking and indoor air quality assessment in the southwestern region of Bangladesh. Heliyon 9(1):e12852. https://doi.org/10.1016/j.heliyon.2023.e12852
5. Almeida MM (2017) Protótipo de um fogão à lenha como alternativa aos modelos tradicionais menos eficientes. Universidade Estadual do Centro-Oeste
6. Arbex AA, Cançado JED, Pereira LAA, Braga ALF, Saldiva PHN (2004) Queima de biomassa e efeitos sobre a saúde. J Bras Pneumol 30(2):158–175
7. Bensch G, Jeuland M, Peters J (2021) Efficient biomass cooking in Africa for climate change mitigation and development. One Earth 4(6):879–890. https://doi.org/10.1016/j.oneear.2021.05.015
8. Boudewijns EA, Trucchi M, van der Kleij RMJJ, Vermond D, Hoffman CM, Chavannes NH, van Schayck OCP, Kirenga B, Brakema EA (2022) Facilitators and barriers to the implementation of improved solid fuel cookstoves and clean fuels in low-income and middle-income countries: an umbrella review. Lancet Planet Health 6(7):e601–e612. https://doi.org/10.1016/S2542-5196(22)00094-8
9. Brand MA, Henne RA, Schein VAS, Pereira ER (2021) Mapeamento dos problemas associados à geração e tratamento das cinzas na combustão da biomassa florestal em caldeira. Problem mapping of the generation and treatment of forest biomass ashes in boiler, pp 1167–1192
10. Brito JO (2007) O uso energético da madeira. Estudos Avançados 21(59):185–193. https://doi.org/10.1590/S0103-40142007000100015
11. Browning KG, Koenig JQ, Checkoway H, Larson TV, Pierson WE (1990) A questionnaire study of respiratory health in areas of high and low ambient wood smoke pollution. Pediatr Asthma Allergy Immunol 4(3):183–191. https://doi.org/10.1089/pai.1990.4.183

12. Carneiro H (2003) Comida e sociedade: Uma história da alimentação. Elsevier, Rio de Janeiro
13. Chen J, Li C, Ristovski Z, Milic A, Gu Y, Islam MS, Wang S, Hao J, Zhang H, He C, Guo H, Fu H, Miljevic B, Morawska L, Thai P, LAM YF, Pereira G, Ding A, Huang X, Dumka UC (2017) A review of biomass burning: emissions and impacts on air quality, health and climate in China. Sci Total Environ 579:1000–1034. https://doi.org/10.1016/j.scitotenv.2016.11.025
14. Chen L, Verrall K, Tong S (2006) Air particulate pollution due to bushfires and respiratory hospital admissions in Brisbane, Australia. Int J Environ Health Res 16(3):181–191. https://doi.org/10.1080/09603120600641334
15. Chew FT, Ooi BC, Hui JKS, Saharom R, Goh DYT, Lee BW (1995) Singapore's haze and acute asthma in children. The Lancet 346(8987):1427. https://doi.org/10.1016/S0140-6736(95)92443-4
16. Dutta A, Ray MR, Banerjee A (2012) Systemic inflammatory changes and increased oxidative stress in rural Indian women cooking with biomass fuels. Toxicol Appl Pharmacol 261(3):255–262. https://doi.org/10.1016/j.taap.2012.04.004
17. Enyew HD, Mereta ST, Hailu AB (2021) Biomass fuel use and acute respiratory infection among children younger than 5 years in Ethiopia: a systematic review and meta-analysis. Public Health 193:29–40. https://doi.org/10.1016/j.puhe.2020.12.016
18. Fachinger F, Drewnick F, Borrmann S (2021) How villages contribute to their local air quality—the influence of traffic- and biomass combustion-related emissions assessed by mobile mappings of PM and its components. Atmos Environ 263:118648. https://doi.org/10.1016/j.atmosenv.2021.118648
19. FAO F and AO of the UN (2022) Renewable energy for agri-food systems
20. Ghorashi SA, Khandelwal B (2023) Toward the ultra-clean and highly efficient biomass-fired heaters. A review. Renew Energy 205:631–647. https://doi.org/10.1016/j.renene.2023.01.109
21. Gioda A, Tonietto GB, de Leon AP (2019) Exposição ao uso da lenha para cocção no Brasil e sua relação com os agravos à saúde da população. Cien Saude Colet 24(8):3079–3088. https://doi.org/10.1590/1413-81232018248.23492017
22. Gordon SB, Bruce NG, Grigg J, Hibberd PL, Kurmi OP, Lam KH, Mortimer K, Asante KP, Balakrishnan K, Balmes J, Bar-Zeev N, Bates MN, Breysse PN, Buist S, Chen Z, Havens D, Jack D, Jindal S, Kan H, Mehta S, Moschovis P, Naeher L, Patel A, Perez-Padilla R, Pope D, Rylance J, Semple S, Martin WJ (2014) Respiratory risks from household air pollution in low and middle income countries. Lancet Respir Med 2(10):823–860. https://doi.org/10.1016/S2213-2600(14)70168-7
23. Hoang AT, Nizetic S, Ong HC, Chong CT, Atabani AE, Pham VV (2021) Acid-based lignocellulosic biomass biorefinery for bioenergy production: Advantages, application constraints, and perspectives. J Environ Manage 296:113194. https://doi.org/10.1016/j.jenvman.2021.113194
24. Jewitt S, Smallman-Raynor M, Binaya KC, Robinson B, Adhikari P, Evans C, Karmacharya BM, Bolton CE, Hall IP (2022) Domesticating cleaner cookstoves for improved respiratory health: using approaches from the sanitation sector to explore the adoption and sustained use of improved cooking technologies in Nepal. Soc Sci Med 308:115201. https://doi.org/10.1016/j.socscimed.2022.115201
25. Kajumba PK, Okello D, Nyeinga K, Nydal OJ (2022) Assessment of the energy needs for cooking local food in Uganda: a strategy for sizing thermal energy storage with cooker system. Energy Sustain Dev 67:67–80. https://doi.org/10.1016/j.esd.2022.01.005
26. Kim Y, Knowles S, Manley J, Radoias V (2017) Long-run health consequences of air pollution: evidence from Indonesia's forest fires of 1997. Econ Hum Biol 26:186–198. https://doi.org/10.1016/j.ehb.2017.03.006
27. Krecl P, Targino AC, Lara C, Oukawa GY, Soares J, Mollinedo EM (2023) Detecting local and regional air pollution from biomass burning at a suburban site. Atmos Environ 297:119591. https://doi.org/10.1016/j.atmosenv.2023.119591
28. Kshirsagar MP, Kalamkar VR (2014) A comprehensive review on biomass cookstoves and a systematic approach for modern cookstove design. Renew Sustain Energy Rev 30:580–603. https://doi.org/10.1016/j.rser.2013.10.039

29. Lage S, Gentili FG (2023) Chemical composition and species identification of microalgal biomass grown at pilot-scale with municipal wastewater and CO_2 from flue gases. Chemosphere 313:137344. https://doi.org/10.1016/j.chemosphere.2022.137344
30. Lupepsa BF, Machado G (2019) Fogão à lenha portátil metálico de tecnologia melhorada para o menor consumo de lenha. ENCICLOPÉDIA Biosf 16:2337–2343. https://doi.org/10.18677/encibio
31. Laumbach RJ, Kipen HM (2012) Respiratory health effects of air pollution: update on biomass smoke and traffic pollution. J Allergy Clin Immunol 129(1):3–11. https://doi.org/10.1016/j.jaci.2011.11.021
32. Lenz L, Bensch G, Chartier R, Kane M, Ankel-Peters J, Jeuland M (2023) Releasing the killer from the kitchen? Ventilation and air pollution from biomass cooking. Dev Eng 8:100108. https://doi.org/10.1016/j.deveng.2023.100108
33. Li L, Cheng Y, Dai Q, Liu B, Wu J, Bi X, Choe T-H, Feng Y (2022) Chemical characterization and health risk assessment of VOCs and PM2.5-bound PAHs emitted from typical Chinese residential cooking. Atmos Environ 291:119392. https://doi.org/10.1016/j.atmosenv.2022.119392
34. Liao W, Liu X, Kang N, Song Y, Wang L, Yuchi Y, Huo W, Mao Z, Hou J, Wang C (2023) Associations of cooking fuel types and daily cooking duration with sleep quality in rural adults: effect modification of kitchen ventilation. Sci Total Environ 854:158827. https://doi.org/10.1016/j.scitotenv.2022.158827
35. Lim SS, Vos T, Flaxman AD, Danaei G, Shibuya K, Adair-Rohani H, AlMazroa MA, Amann M, Anderson HR, Andrews KG, Aryee M, Atkinson C, Bacchus LJ, Bahalim AN, Balakrishnan K, Balmes J, Barker-Collo S, Baxter A, Bell ML, Blore JD, Blyth F, Bonner C, Borges G, Bourne R, Boussinesq M, Brauer M, Brooks P, Bruce NG, Brunekreef B, Bryan-Hancock C, Bucello C, Buchbinder R, Bull F, Burnett RT, Byers TE, Calabria B, Carapetis J, Carnahan E, Chafe Z, Charlson F, Chen H, Chen JS, Cheng AT-A, Child JC, Cohen A, Colson KE, Cowie BC, Darby S, Darling S, Davis A, Degenhardt L, Dentener F, Des Jarlais DC, Devries K, Dherani M, Ding EL, Dorsey ER, Driscoll T, Edmond K, Ali SE, Engell RE, Erwin PJ, Fahimi S, Falder G, Farzadfar F, Ferrari A, Finucane MM, Flaxman S, Fowkes FGR, Freedman G, Freeman MK, Gakidou E, Ghosh S, Giovannucci E, Gmel G, Graham K, Grainger R, Grant B, Gunnell D, Gutierrez HR, Hall W, Hoek HW, Hogan A, Hosgood HD, Hoy D, Hu H, Hubbell BJ, Hutchings SJ, Ibeanusi SE, Jacklyn GL, Jasrasaria R, Jonas JB, Kan H, Kanis JA, Kassebaum N, Kawakami N, Khang Y-H, Khatibzadeh S, Khoo J-P, Kok C, Laden F, Lalloo R, Lan Q, Lathlean T, Leasher JL, Leigh J, Li Y, Lin JK, Lipshultz SE, London S, Lozano R, Lu Y, Mak J, Malekzadeh R, Mallinger L, Marcenes W, March L, Marks R, Martin R, McGale P, McGrath J, Mehta S, Memish ZA, Mensah GA, Merriman TR, Micha R, Michaud C, Mishra V, Hanafiah KM, Mokdad AA, Morawska L, Mozaffarian D, Murphy T, Naghavi M, Neal B, Nelson PK, Nolla JM, Norman R, Olives C, Omer SB, Orchard J, Osborne R, Ostro B, Page A, Pandey KD, Parry CD, Passmore E, Patra J, Pearce N, Pelizzari PM, Petzold M, Phillips MR, Pope D, Pope CA, Powles J, Rao M, Razavi H, Rehfuess EA, Rehm JT, Ritz B, Rivara FP, Roberts T, Robinson C, Rodriguez-Portales JA, Romieu I, Room R, Rosenfeld LC, Roy A, Rushton L, Salomon JA, Sampson U, Sanchez-Riera L, Sanman E, Sapkota A, Seedat S, Shi P, Shield K, Shivakoti R, Singh GM, Sleet DA, Smith E, Smith KR, Stapelberg NJ, Steenland K, Stöckl H, Stovner LJ, Straif K, Straney L, Thurston GD, Tran JH, Van Dingenen R, van Donkelaar A, Veerman JL, Vijayakumar L, Weintraub R, Weissman MM, White RA, Whiteford H, Wiersma ST, Wilkinson JD, Williams HC, Williams W, Wilson N, Woolf AD, Yip P, Zielinski JM, Lopez AD, Murray CJ, Ezzati M (2012) A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. The Lancet 380(9859):2224–2260. https://doi.org/10.1016/S0140-6736(12)61766-8
36. Logue JM, Klepeis NE, Lobscheid AB, Singer BC (2014) Pollutant exposures from natural gas cooking burners: a simulation-based assessment for Southern California. Environ Health Perspect 122(1):43–50. https://doi.org/10.1289/ehp.1306673

37. Manoj Kumar, Sachin Kumar, Tyagi SK (2013) Design, development and technological advancement in the biomass cookstoves: a review. Renew Sustain Energy Rev 26:265–285. https://doi.org/10.1016/j.rser.2013.05.010
38. Medeiros A, Gouveia N (2005) Relação entre baixo peso ao nascer e a poluição do ar no Município de São Paulo. Rev Saude Publica 39(6):965–972. https://doi.org/10.1590/S0034-89102005000600015
39. Mitra P, Chakraborty D, Nayek S, Kundu S, Mishra D, Dan U, Mondal NK (2023) Biomass using tribal women exhibited respiratory symptoms, hypertensive risks and abnormal pulmonary function. Chemosphere 311:136995. https://doi.org/10.1016/j.chemosphere.2022.136995
40. Moraes AM De, Trigoso F, Martins G (2008) O fogão a lenha no semiárido do Piauí : métodos tradicionais e alternativas tecnológicas eficientes
41. Moreira MAC, Barbosa MA, Jardim JR, Queiroz MCC, Inácio LU (2013) Doença pulmonar obstrutiva crônica em mulheres expostas à fumaça de fogão à lenha. Rev Assoc Med Bras 59(6):607–613. https://doi.org/10.1016/j.ramb.2013.09.001
42. Munyao CM, Kiptoo KKG, Odinga C, Simiyu GM (2022) Assessment of improved biomass cookstove technologies and kitchen characteristics on indoor air quality and fuel consumption in rural settings of western, Kenya. Eur J Health Sci 7(5):58–83. https://doi.org/10.47672/ejhs.1228
43. Muralidharan V, Sussan T, Limaye S, Koehler K, Williams D, Rule A, Juvekar S, Breysse P, Salvi S, Biswal S (2015) Field testing of alternative cookstove performance in a rural setting of western India. Int J Environ Res Public Health 12(2):1773–1787. https://doi.org/10.3390/ijerph120201773
44. Naeher LP, Brauer M, Lipsett M, Zelikoff JT, Simpson CD, Koenig JQ, Smith KR (2007) Woodsmoke health effects: a review. Inhal Toxicol 19(1):67–106. https://doi.org/10.1080/08958370600985875
45. Nix E, Betang E, Baame M, Abbott M, Saligari S, Shupler M, Čukić I, Puzzolo E, Pope D, Mbatchou B, Anderson de Cuevas R (2022) Complex dynamics in sustaining clean cooking and food access through a pandemic: A COVID-19 impact study in peri-urban Cameroon. Energy Sustain Dev 71:167–175. https://doi.org/10.1016/j.esd.2022.09.017
46. Nuño N, Mäusezahl D, Hartinger SM, Riley-Powell AR, Verastegui H, Wolf J, Muela J, Paz-Soldán VA (2023) Acceptance and uptake of improved biomass cookstoves in Peru—learning from system level approaches to transform large-scale cooking interventions. Energy Res Soc Sci 97:102958. https://doi.org/10.1016/j.erss.2023.102958
47. Obernberger I, Biedermann F, Widmann W, Riedl R (1997) Concentrations of inorganic elements in biomass fuels and recovery in the different ash fractions. Biomass Bioenergy 12(3):211–224. https://doi.org/10.1016/S0961-9534(96)00051-7
48. Olave RJ, Forbes EGA, Johnston CR, Relf J (2017) Particulate and gaseous emissions from different wood fuels during combustion in a small-scale biomass heating system. Atmos Environ 157:49–58. https://doi.org/10.1016/j.atmosenv.2017.03.003
49. Padhi A, Bansal M, Habib G, Samiksha S, Raman RS (2022) Physical, chemical and optical properties of PM2.5 and gaseous emissions from cooking with biomass fuel in the Indo-Gangetic Plain. Sci Total Environ 841:156730. https://doi.org/10.1016/j.scitotenv.2022.156730
50. Panwar NL (2010) Performance evaluation of developed domestic cook stove with Jatropha Shell. Waste Biomass Valorization 1(3):309–314. https://doi.org/10.1007/s12649-010-9040-8
51. Park D, Barabad ML, Lee G, Kwon S-B, Cho Y, Lee D, Cho K, Lee K (2013) Emission characteristics of particulate matter and volatile organic compounds in cow dung combustion. Environ Sci Technol 47(22):12952–12957. https://doi.org/10.1021/es402822e
52. Pratali L, Marinoni A, Cogo A, Ujka K, Gilardoni S, Bernardi E, Bonasoni P, Bruno RM, Bastiani L, Vuillermoz E, Sdringola P, Fuzzi S (2019) Indoor air pollution exposure effects on lung and cardiovascular health in the High Himalayas, Nepal: an observational study. Eur J Intern Med 61:81–87. https://doi.org/10.1016/j.ejim.2018.10.023

53. Preble CV, Hadley OL, Gadgil AJ, Kirchstetter TW (2014) Emissions and climate-relevant optical properties of pollutants emitted from a three-stone fire and the Berkeley-Darfur stove tested under laboratory conditions. Environ Sci Technol 48(11):6484–6491. https://doi.org/10.1021/es5002715
54. Price-Allison A, Lea-Langton AR, Mitchell EJS, Gudka B, Jones JM, Mason PE, Williams A (2019) Emissions performance of high moisture wood fuels burned in a residential stove. Fuel 239:1038–1045. https://doi.org/10.1016/j.fuel.2018.11.090
55. Qin Z, Zhuang Q, Cai X, He Y, Huang Y, Jiang D, Lin E, Liu Y, Tang Y, Wang MQ (2018) Biomass and biofuels in China: toward bioenergy resource potentials and their impacts on the environment. Renew Sustain Energy Rev 82:2387–2400. https://doi.org/10.1016/j.rser.2017.08.073
56. Rhofita EI, Rachmat R, Meyer M, Montastruc L (2022) Mapping analysis of biomass residue valorization as the future green energy generation in Indonesia. J Clean Prod 354:131667. https://doi.org/10.1016/j.jclepro.2022.131667
57. Ribeiro IO, do Santos EO, Batista CE, Fernandes KS, Ye J, Medeiros AS, e Oliveira RL, de Sá SS, de Sousa TR, Kayano MT, Andreoli RV, Machado CMD, Surratt JD, Junior SD, Martin ST, de Souza RAF (2020) Impact of biomass burning on a metropolitan area in the Amazon during the 2015 El Niño: the enhancement of carbon monoxide and levoglucosan concentrations. Environ Pollut 260:114029. https://doi.org/10.1016/j.envpol.2020.114029
58. Saravanna JY, Kantamnen R, Fasil N, Sivamani S, Hariram V, Micha Premkumar T, Mohan T (2017) Modelling and analysis of water heating using recovered waste heat from hot flue gases of Chulha. ARPN J Eng Appl Sci 12(21):6164–6171
59. Santos GHF, do Nascimento RS, Alves GM (2017) Biomassa como energia renoáel no Brasil. UNINGÀ Rev 29:6–13
60. Santos PR, Pereira G, da Silva Cardozo F, Mataveli GAV, Moraes EC (2021) Desenvolvimento e implementação do ciclo diurno da queima de biomassa no PREP-CHEM-SRC. Geography Department University of Sao Paulo 41:e174236. https://doi.org/10.11606/eISSN.2236-2878.rdg.2021.174236
61. Sartor K, Restivo Y, Ngendakumana P, Dewallef P (2014) Prediction of SO_x and NO_x emissions from a medium size biomass boiler. Biomass Bioenergy 65:91–100. https://doi.org/10.1016/j.biombioe.2014.04.013
62. Sha Q, Lu M, Huang Z, Yuan Z, Jia G, Xiao X, Wu Y, Zhang Z, Li C, Zhong Z, Zheng J (2019) Anthropogenic atmospheric toxic metals emission inventory and its spatial characteristics in Guangdong province, China. Sci Total Environ 670:1146–1158. https://doi.org/10.1016/j.scitotenv.2019.03.206
63. Shen G, Lin W, Chen Y, Yue D, Liu Z, Yang C (2015) Factors influencing the adoption and sustainable use of clean fuels and cookstoves in China—a Chinese literature review. Renew Sustain Energy Rev 51:741–750. https://doi.org/10.1016/j.rser.2015.06.049
64. Shen G, Tao S, Chen Y, Zhang Y, Wei S, Xue M, Wang B, Wang R, Lu Y, Li W, Shen H, Huang Y, Chen H (2013) Emission characteristics for polycyclic aromatic hydrocarbons from solid fuels burned in domestic stoves in rural China. Environ Sci Technol 47(24):14485–14494. https://doi.org/10.1021/es403110b
65. Shi Y, Xi Z, Simayi M, Li J, Xie S (2020) Scattered coal is the largest source of ambient volatile organic compounds during the heating season in Beijing. Atmos Chem Phys 20(15):9351–9369. https://doi.org/10.5194/acp-20-9351-2020
66. Smith KR, Apte MG, Yuqing M, Wongsekiarttirat W, Kulkarni A (1994) Air pollution and the energy ladder in Asian cities. Energy 19(5):587–600. https://doi.org/10.1016/0360-5442(94)90054-X
67. Smith KR, Ezzati M (2005) How environmental health risks change with development: the epidemiologic and environmental risk transitions revisited. Annu Rev Environ Resour 30(1):291–333. https://doi.org/10.1146/annurev.energy.30.050504.144424
68. Smith MA, Jalaludin B, Byles JE, Lim L, Leeder SR (1996) Asthma presentations to emergency departments in Western Sydney during the January 1994 Bushfires. Int J Epidemiol 25(6):1227–1236. https://doi.org/10.1093/ije/25.6.1227

69. Sousa AC, Pastorinho MR, Masjedi MR, Urrutia-Pereira M, Arrais M, Nunes E, To T, Ferreira AJ, Robalo-Cordeiro C, Borrego C, Teixeira JP, Taborda-Barata L (2022) Issue 1—"Update on adverse respiratory effects of outdoor air pollution" Part 2): outdoor air pollution and respiratory diseases: perspectives from Angola, Brazil, Canada, Iran, Mozambique and Portugal. Pulmonology 28(5):376–395. https://doi.org/10.1016/j.pulmoe.2021.12.007
70. Still D, Bentson S, Li H (2015) Results of laboratory testing of 15 cookstove designs in accordance with the ISO/IWA tiers of performance. EcoHealth 12(1):12–24. https://doi.org/10.1007/s10393-014-0955-6
71. Streets D, Hao J, Wu Y, Jiang J, Chan M, Tian H, Feng X (2005) Anthropogenic mercury emissions in China. Atmos Environ 39(40):7789–7806. https://doi.org/10.1016/j.atmosenv.2005.08.029
72. Sullivan J, Sheppard L, Schreuder A, Ishikawa N, Siscovick D, Kaufman J (2005) Relation between short-term fine-particulate matter exposure and onset of myocardial infarction. Epidemiology 16(1):41–48. https://doi.org/10.1097/01.ede.0000147116.34813.56
73. Sun Y, Wang S, Yang Q, Li J, Wang L, Zhang S, Yang H, Chen H (2023) Environmental impact assessment of VOC emissions from biomass gasification power generation system based on life cycle analysis. Fuel 335:126905. https://doi.org/10.1016/j.fuel.2022.126905
74. Sutar KB, Kohli S, Ravi MR, Ray A (2015) Biomass cookstoves: a review of technical aspects. Renew Sustain Energy Rev 41:1128–1166. https://doi.org/10.1016/j.rser.2014.09.003
75. Sutherland ER, Make BJ, Vedal S, Zhang L, Dutton SJ, Murphy JR, Silkoff PE (2005) Wildfire smoke and respiratory symptoms in patients with chronic obstructive pulmonary disease. J Allergy Clin Immunol 115(2):420–422. https://doi.org/10.1016/j.jaci.2004.11.030
76. Tan WC, Qiu D, Liam BL, Ng TP, Lee SH, van Eeden SF, D'Yachkova Y, Hogg JC (2000) The human bone marrow response to acute air pollution caused by forest fires. Am J Respir Crit Care Med 161(4):1213–1217. https://doi.org/10.1164/ajrccm.161.4.9904084
77. Tepper A, Comstock GW, Levine M (1991) A longitudinal study of pulmonary function in fire fighters. Am J Ind Med 20(3):307–316. https://doi.org/10.1002/ajim.4700200304
78. Tesfaigzi Y (2002) Health effects of subchronic exposure to low levels of wood smoke in rats. Toxicol Sci 65(1):115–125. https://doi.org/10.1093/toxsci/65.1.115
79. Tesfaldet YT, Chanpiwat P (2023) The effects of meteorology and biomass burning on urban air quality: the case of Bangkok. Urban Clim 49:101441. https://doi.org/10.1016/j.uclim.2023.101441
80. Torigoe K, Hasegawa S, Numata O, Yazaki S, Matsunaga M, Boku N, Hiura M, Ino H (2000) Influence of emission from rice straw burning on bronchial asthma in children. Pediatr Int 42(2):143–150. https://doi.org/10.1046/j.1442-200x.2000.01196.x
81. Traynor GW, Apte MG, Carruthers AR, Dillworth JF, Grimsrud DT, Gundel LA (1987) Indoor air pollution due to emissions from wood-burning stoves. Environ Sci Technol 21(7):691–697. https://doi.org/10.1021/es00161a010
82. Triche EW, Belanger K, Bracken MB, Beckett WS, Holford TR, Gent JF, McSharry J-E, Leaderer BP (2005) Indoor heating sources and respiratory symptoms in nonsmoking women. Epidemiology 16(3):377–384. https://doi.org/10.1097/01.ede.0000158225.44414.85
83. Vassilev SV, Baxter D, Andersen LK, Vassileva CG (2010) An overview of the chemical composition of biomass. Fuel 89(5):913–933. https://doi.org/10.1016/j.fuel.2009.10.022
84. Wamalwa P, Okoti M, Mutembei H, Mandila B, Kisiangani B (2022) Adoption of improved biomass cook stoves: case study of Baringo and West Pokot Counties in Kenya. J Sustain Bioenergy Syst 12(02):21–36. https://doi.org/10.4236/jsbs.2022.122003
85. Wang L, Wang S, Zhang L, Wang Y, Zhang Y, Nielsen C, McElroy MB, Hao J (2014) Source apportionment of atmospheric mercury pollution in China using the GEOS-Chem model. Environ Pollut 190:166–175. https://doi.org/10.1016/j.envpol.2014.03.011
86. Wei W, Zhang W, Hu D, Ou L, Tong Y, Shen G, Shen H, Wang X (2012) Emissions of carbon monoxide and carbon dioxide from uncompressed and pelletized biomass fuel burning in typical household stoves in China. Atmos Environ 56:136–142. https://doi.org/10.1016/j.atmosenv.2012.03.060
87. WHO (2014) Guidelines for indoor air quality: household fuel combustion

88. Witt MB (2005) An improved wood cookstove: Harnessing fan driven forced draft for cleaner combustion. Hartford CT Trinity Coll
89. Wu J, Kong S, Wu F, Cheng Y, Zheng S, Yan Q, Zheng H, Yang G, Zheng M, Liu D, Zhao D, Qi S (2018) Estimating the open biomass burning emissions in central and eastern China from 2003 to 2015 based on satellite observation. Atmos Chem Phys 18(16):11623–11646. https://doi.org/10.5194/acp-18-11623-2018
90. Xing X, Zhou Y, Lang J, Chen D, Cheng S, Han L, Huang D, Zhang Y (2018) Spatiotemporal variation of domestic biomass burning emissions in rural China based on a new estimation of fuel consumption. Sci Total Environ 626:274–286. https://doi.org/10.1016/j.scitotenv.2018.01.048
91. Xu HM, Cao JJ, Ho KF, Ding H, Han YM, Wang GH, Chow JC, Watson JG, Khol SD, Qiang J, Li WT (2012) Lead concentrations in fine particulate matter after the phasing out of leaded gasoline in Xi'an, China. Atmos Environ 46:217–224. https://doi.org/10.1016/j.atmosenv.2011.09.078
92. Xu J-W, Martin RV, Henderson BH, Meng J, Öztaner YB, Hand JL, Hakami A, Strum M, Phillips SB (2019) Simulation of airborne trace metals in fine particulate matter over North America. Atmos Environ 214:116883. https://doi.org/10.1016/j.atmosenv.2019.116883
93. Yadav IC, Linthoingambi Devi N, Li J, Syed JH, Zhang G, Watanabe H (2017) Biomass burning in Indo-China peninsula and its impacts on regional air quality and global climate change-a review. Environ Pollut 227:414–427. https://doi.org/10.1016/j.envpol.2017.04.085
94. Yan Y, Lin J, Chen J, Hu L (2016) Improved simulation of tropospheric ozone by a global-multi-regional two-way coupling model system. Atmos Chem Phys 16(4):2381–2400. https://doi.org/10.5194/acp-16-2381-2016
95. Yang N (2010) Fuel-efficient stoves: a comparison of Berkeley-Darfur stoves to three-stone fires 1–17
96. Yu O, Sheppard L, Lumley T, Koenig JQ, Shapiro GG (2000) Effects of ambient air pollution on asthma symptoms in Seattle-area children enrolled in the CAMP study. Environ Health Perspect 108(12):1209–1214. https://doi.org/10.1289/ehp.001081209
97. Zelikoff JT, Chen LC, Cohen MD, Schlesinger RB (2002) The toxicology of inhaled woodsmoke. J Toxicol Environ Health Part B 5(3):269–282. https://doi.org/10.1080/10937400290070062
98. Zhang R, Xu G, Li B, Wang Z, Gao J, Li J, Sun Y, Xu G (2023) Analysis of the pollution emission system of large-scale combustion of biomass briquette fuel in China. Process Saf Environ Prot 169:928–936. https://doi.org/10.1016/j.psep.2022.11.088
99. Zheng S, Shen H, Shen G, Chen Y, Ma J, Cheng H, Tao S (2022) Vertically-resolved indoor measurements of air pollution during Chinese cooking. Environ Sci Ecotechnol 12:100200. https://doi.org/10.1016/j.ese.2022.100200
100. Zong Z, Shi X, Sun Z, Tian C, Li J, Fang Y, Gao H, Zhang G (2022) Nitrogen isotopic composition of NO_x from residential biomass burning and coal combustion in North China. Environ Pollut 304:119238. https://doi.org/10.1016/j.envpol.2022.119238

Combustion Equipment Used in Food Preparation Around the World: What Is Its Influence on Air Pollution and How to Mitigate These Harmful Effects?

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Abstract The use of wood or biomass-burning stoves for cooking is a common practice in many countries. Approximately 3 billion people cook and heat their homes with fires and stoves that burn biomass (wood, animal dung or agricultural waste) and charcoal. However, this practice can lead to serious environmental and public health problems, as the inefficient burning of biomass in these stoves produces large amounts of polluting gases and fine particles that are harmful both to those using the equipment and to the environment. To mitigate these impacts, there are several strategies that can be adopted. One of them is the use of more efficient stoves that consume less fuel and produce less smoke. These stoves can be of various types, from the simplest ones that use only a small amount of wood, to the most advanced ones that have combustion systems and filters to reduce the emissions of polluting gases. In addition, there are also other alternatives, such as the use of solar ovens, which use the energy of the sun to cook food, or the use of oven filters, which can

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be installed in existing equipment to reduce the emission of polluting gases. Despite these alternatives, there are still many gaps in scientific knowledge about the use of wood or biomass-burning stoves for cooking. In this context, the objective of this chapter is to address how the equipment used in food preparation leads to a significant increase in gas emissions. We will also address alternatives to overcome the reality of using rudimentary technologies, such as solar ovens and oven filters. Finally, we will show the existing gaps within this niche of study and what research should focus on in future studies.

Keywords Food safety · Biomass · Household energy · Environmental health

1 Introduction

The use of wood or biomass-burning stoves for cooking is a common practice in various regions of the world, especially in rural and low-income communities. These stoves can range from the most rudimentary, such as clay stoves and open fires, to more modern equipment, such as wood-fired ovens and stoves with more efficient burners. However, despite being considered a more accessible and economical alternative, these stoves can generate serious environmental and public health impacts.

Since ancient times, wood or biomass-burning stoves have been used worldwide. In Africa, for example, the "jiko" is a type of clay stove used for cooking food [64]. In Asia, the use of "tandoors" or cylindrical clay ovens to cook bread and other foods is common [33]. In Latin America, wood-burning stoves are often used in rural areas. In recent years, more modern equipment has emerged, such as stoves with more efficient burners and wood-fired ovens with thermal insulation, which reduce the amount of fuel needed to cook food.

However, despite the economic and cultural benefits, the use of wood or biomass equipment can generate serious environmental and public health impacts. The combustion of biomass produces large amounts of polluting gases that contribute to the greenhouse effect and climate change [51]. In addition, inhalation of smoke generated by these equipments can cause serious respiratory problems, such as lung diseases and lung cancer [103]. Among the main gases emitted by wood or biomass equipment are carbon dioxide, methane, and carbon monoxide [51]. Carbon dioxide is one of the main greenhouse gases, while methane is even more potent in terms of greenhouse effect. Carbon monoxide is a toxic gas that can cause poisoning and even death in high concentrations.

There are several strategies to mitigate gas emissions from wood or biomass cooking equipment. One of them is the adoption of more efficient stoves, which consume less fuel and produce less smoke. Another strategy is the use of renewable energy sources, such as solar energy or biogas, for food preparation [100]. Additionally, community awareness about the environmental and public health impacts of using wood or biomass equipment is crucial for the adoption of more sustainable practices. In this sense, the objective of this chapter is to address the main biomass-based equipment used in food preparation, from the oldest to the most modern, and their influence on gas emissions and climate change. We will also present the latest technologies for wood or biomass equipment in food preparation, with the aim of identifying innovative and sustainable solutions to reduce emissions and improve the energy efficiency of these devices. Moreover, we will present strategies to mitigate gas emissions from these cooking devices, taking into account technical, economic, and social aspects. Finally, we will also present scientific advances in this research field to determine existing gaps and what needs to be the focus of study in this area in the coming years.

2 Equipment for Food Preparation: History and Technological Advances

The history of stoves begins with the discovery of fire by our ancestors. After archaeological excavations in the village of Zhoukoudian (Chou Kutien), China, it was found that *Homo erectus pekingnensis*, or Peking Man, used biomass fuel inside caves to keep warm about 400,000 years ago [14]. Research conducted at the site later enabled the discovery of burned items such as charcoal, stones, and bones. These findings were widely accepted as the oldest reliable evidence of hominids using fire in the world [12, 78]. During the Paleolithic period, open fires (bonfires) (Fig. 1a) were used for warmth and protection against animal attacks, and only in the Middle Paleolithic period did the use of fire become known for cooking food [66, 102]. One of the earliest cooking methods was to roast meat in a type of oven that consisted of holes in the ground. The fire is made inside the hole with biomass fuels, and only when the flames are extinguished are the meats that are arranged in alternating layers between stones inserted into the pits and finished by covering them with soil (Fig. 1a). These methods are still used in some places today [102].

The initial period, prior to the seventeenth century, was marked by low-energy efficiency stoves with high smoke emissions due to the use of weak materials in their construction, known as “traditional stoves” [66]. The stove took on its basic familiar form about 12,000 years ago with the development of its design, which progressed from an open fire to a closed firebox with the goal of balancing pots on the fire. The

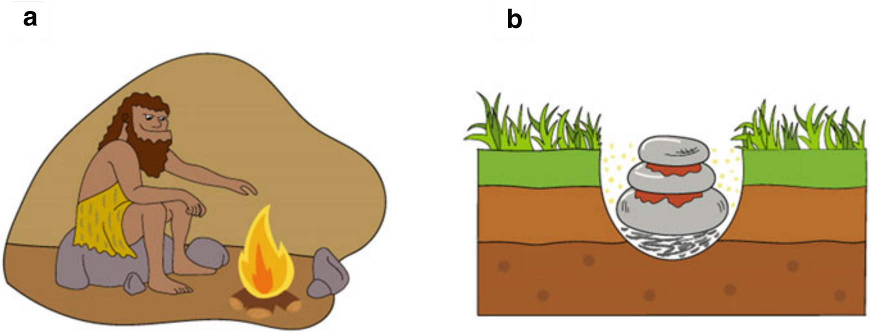

Fig. 1 Bonfire (**a**); Hole fire (**b**) (*Source* The authors 2023)

Fig. 2 Three-stone stove (*Source* The authors 2023)

three-stone wood stove (trempé), the first model of a closed stove and still used today in underdeveloped countries, consists of an arrangement of three similarly shaped and sized stones, which are placed on a flat surface to maintain the stability of the pots that will be placed on top, with biomass arranged in the center of the stones (Fig. 2). Its dimensions are defined relative to the size of the utensil that will be used [66].

With the purpose of obtaining a more efficient stove, models were increasingly improved over time. As time went by, stoves evolved and took on various shapes and sizes, made with different types of materials and adapted to different cultures and needs [59]. With the development of the enclosed fire, the three-stone model became a clay stove in the shape of a "U". In this model, the stove is made with a mixture of clay and straw, fixed to the ground in a "U" shape, modeling a semi-open oven, where the front has an opening for the biomass feed and there may be protrusions on its surface to improve the support of cooking utensils and facilitate air intake (Fig. 3) [66]. The mechanism for improving this model is the induction of secondary air for efficient combustion, as the air prevents the slip of unburned biomass, thus promoting complete burning of the fuel that was used. The first improved clay stove reported in the literature was created in India in 1947 and was called the "Magan Chulha". Aimed at solving problems such as smoke production for health improvement and forest conservation, the model is now produced with blocks of clay and includes curved ducts, a metal grate, and a ceramic chimney attached to conduct the smoke produced during biomass burning [5, 58].

In the 1970s, the global oil crisis brought attention to energy issues [87]. However, during this time, researcher [29] published a report on "Wood: The Other Energy Crisis," which highlighted the unsustainable use of wood in rural areas for domestic activities such as cooking and heating, which he deemed subtle but equally devastating. According to [102] the period between 1970 and 1980 was known as the "first phase" or "first wave" of improved cookstove (IC) development. The primary goal of professionals during this first phase was to achieve more efficient combustion to achieve biomass fuel savings [91]. The energy crisis of the 1970s led to the development of new improved cookstoves through research, introducing models with

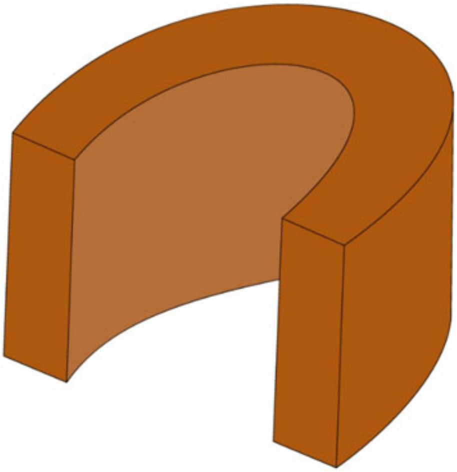

Fig. 3 “U” type stove (*Source* The authors 2023)

low biomass consumption in locations that heavily relied on this fuel for cooking, as attention was focused on environmental and energy conservation issues [30, 39, 66]. It was in this context that the first projects were implemented. After a major earthquake hit Guatemala in 1976, the country received international aid to rebuild destroyed homes, and improvements were made to kitchens. As a result, they developed a stove model called the “Lorena stove,” made with clay blocks filled with a sand-clay mixture (Fig. 4). This stove model soon became popular in Guatemala and other Central American countries due to its efficiency, product promotion, and further research by the Aprovecho Research Center (ARC) [102]. The Lorena stove model has been modified over the years by other IC programs in South Asian countries, where [5] showcases several programs and their respective modifications based on the Guatemala model.

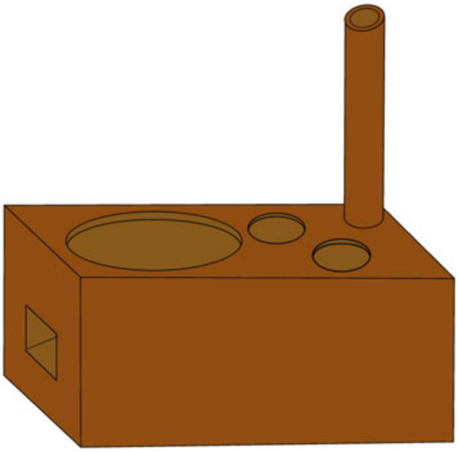

Fig. 4 Lorena stove (*Source* Adapted from [37]

Many of the programs carried out at this time were not accepted by the public since the creation of stoves by experts developed rapidly and extremely technically, without even considering the issue of social context, given that the majority of stove users in the world are women who were not involved in the development process as their empirical knowledge was considered inferior to the technical knowledge of the experts [19, 88].

The beginning of the second phase was marked by two scenarios that changed the course of improved cookstove organizations. Firstly, the understanding that the deficit of wood was not linked to subsistence consumption of rural communities, but rather to deforestation for subsequent cultivation or grazing of livestock, practices linked to agribusiness and which became a threat to energy resources [19, 36, 65, 97]. Secondly, organizations understood the importance of community participation in the planning and development of improved cookstoves, which would result in greater acceptance of the products, since their involvement would make it possible to identify potential problems for that specific community [10, 102].

At this moment, several stove improvement programs were created in various parts of the world, but mainly in underdeveloped countries that had biomass as their main source of energy for domestic activities. The stoves were adapted over the years according to culinary habits and traditions. Improved stoves were developed in various countries around the world, such as Ethiopia, Eritrea, Ghana, Ivory Coast, Kenya, Madagascar, Malawi, Mozambique, Niger, Bangladesh, Indonesia, Nepal, Pakistan, Thailand, Bolivia, Argentina, Cuba, Peru, and Mexico [3]. However, India and China are countries that have developed more widespread programs and are therefore chosen to be explored throughout the chapter.

The Indian National Program on Improved Chulha (NPIC) was established in 1983 and only launched on a full-scale basis in mid-1985 [42]. As previously discussed, the main purpose was to improve the management of energy resources, and the NPIC included several objectives in its project to achieve this goal: (i) conservation of biomass, (ii) removal of kitchen smoke; (iii) updating of deforestation data; (iv) reduction of women's labor-intensive work; and (v) providing opportunities for extra income for local communities [5]. Despite the program having 80 different models, all can be categorized into 6 different groups: (a) fixed mud stove, with and without a chimney, (b) fixed mud stove coated with ceramics, with or without a chimney; (c) portable metal stove without a chimney; (d) portable metal stove coated with ceramics, without a chimney; and (e) portable stove with a separate chimney system [3]. The "Astra Stove" model was designed by the Centre for Sustainable Technologies at the Indian Institute of Science in Bangalore. The Astra stove is considered one of the best stoves available in the country, offering more than 40% efficiency [53]. These results were achieved through improvements such as controlled entry of primary and secondary air, facilitating proper combustion, inclusion of a chimney with appropriate measurements, and the overall design [5]. In addition to improvements in efficient combustion, the NPIC program demonstrated other progress, such as female empowerment, and some states promoted improvements in cooking through these popular programs [3].

As discussed earlier, each stove model corresponds to the local reality of the community. The most popular ICs in Sri Lanka, a country located south of India, is the "Anagi Stove" introduced by the Ceylon Electricity Board (CEB) in 1986. This stove is built with two pieces of clay pot and can be fueled by wood, leaves, coconut shells, and other biomass residues. Its unique design was developed to meet the needs and culinary habits of the local culture in Sri Lanka [5].

Another program with a high rate of dissemination of stoves was the Chinese National Improved Stove Program (NISP), created by the government in the early 1980s and considered the world's largest public financing initiative for stove improvements. With more than 100 million units, the NISP is one of the most successful programs [106]. The FL model is a stove developed based on local cuisine and built with brick, cement, and cast iron. This stove has two design models: the FL Partial Composite Stove (FL-PCS) and the FL Complete Composite Stove (FL-CCS). The difference between the models is in the material they are constructed with, the FL-PCS has the combustion chamber and cast iron grate while the other parts are self-constructed, whereas the FL-CCS is entirely made of cast iron and includes a ready-to-install chimney [105].

As previously discussed, the second phase was mainly characterized by the need to save wood and reduce hard work, but reducing smoke was a secondary issue [91]. After research, it was found that the use of chimneys only shifted the smoke problem outside the houses but did not eliminate it [94]. As a consequence, in the early 1990s, it was observed that the use of wood for cooking food could pose health risks due to the smoke produced during combustion, and in this problem, agents realized that the use of ICs could bring, once again, a solution to this impasse [34, 92]. At the World Summit on Sustainable Development held in Johannesburg in 2002, the U.S. Environmental Protection Agency (EPA) announced the "Partnership for Clean Indoor Air" project aimed at mitigating the health risks of people using biomass fuels in their homes [13]. In this third phase, improved stove programs were improved with an emphasis on health issues [7]. Single-pot metal stoves without chimneys were the most launched models during this period [59].

As a result, the Indian government, after the country's Ministry of New and Renewable Energy (MNRE) considered the NPIC a failure, relaunched a "National Biomass Stove Initiative" project in December 2009 with the main objective of increasing the use of improved biomass stoves, but with more efficient, longer-lasting, effective, and easy-to-use products. Other objectives of the program are to develop and implement biomass stoves that provide cleaner energy, reduce the hard work of women and children who use traditional Chulhas, and reduce climate change by reducing black carbon emissions during biomass burning. The project has more than 40 different models divided into fixed and portable types (natural and forced draft) and can be made of metal, ceramic, and terracotta/ceramic [70].

Despite technological advancements in improving wood stoves, researchers around the world have been seeking more sustainable and low-cost alternatives for the development of cooking equipment. This interest is due to three important factors: (i) improving the quality of life of the population; (ii) reducing the emission of polluting gases released during biomass burning that influence climate change; and (iii) seeking renewable energy sources in order to reduce the use of petroleum and natural gas. These points are directly related to the Sustainable Development Goals (SDGs) established by the WHO (World Health Organization), specifically: 3—Good health and well-being; 7—Affordable and clean energy; 10—Reduced inequalities; 12—Responsible consumption and production; and 13—Climate action. Based on this, solar ovens stand out as a recent, accessible, and efficient technology for cooking that can reduce the use of wood stoves and consequently their social and environmental impacts [27, 74].

Solar stoves, also known as solar ovens, are devices that use solar radiation as the primary source of energy, mainly for cooking food, but also have potential for important processes such as pasteurization and sterilization [44, 46] Solar stoves are based on the principle of concentrating solar energy and using this heat for cooking food, without the need for any other fuel besides sunlight to operate these devices [77]. It is reported that the first solar ovens were developed in the eighteenth century, with physicist Horace de Saussure being the first researcher to use this equipment to cook fruits [20, 84]. However, according to [84], the World Wars and the energy crisis intensified the interest in using these types of stoves.

Considering that around 2.4 billion people, mainly located in poor or developing countries, cook using polluting fuels [22] world organizations such as the Solar Cookers International (SCI) have intensified efforts to introduce the use of solar stoves in the daily lives of these populations for sustainable and environmentally friendly cooking, with the main mission of improving human health, economic well-being, and the environment [4, 86].

Solar cookers can be found in different shapes, varying according to the manufacturers and the improvements made by researchers focused on developing more efficient devices. However, solar cookers fall into two categories based on the heat transfer method, namely the direct method, which includes box-type cookers, and the indirect method, which includes solar panel and parabolic cookers. Box-type solar cookers are characterized as an isolated device with a multiple or single glass lid, which has reflectors that direct the sun's rays into the box. The interior of the box is coated with black paint to improve the absorption capabilities of the solar light [71]. According to [20], the first containers created for cooking food using solar radiation were of the box type. However, it was only in the 1970s that an efficient and viable box-type solar oven model for domestic use was developed by Barbara Kerr, a resident of Arizona in the United States [84]. Generally, this cooker model can reach temperatures of up to 100 °C, a characteristic that enables boiling food [107]. However, the main limitation of this device is the lack of energy storage, which makes it difficult to use when it is not receiving solar radiation. Within this context, research is being developed mainly to improve the characteristics of these cookers in order to make them more efficient. Reference [21], when evaluating solar cookers with and without thermal energy storage, concluded that devices made up of Bayburt stone are an excellent material to complement box-type cookers due to their constant, efficient, and continuous cooking ability, as well as their capacity for thermal energy storage for different periods of the day. The advantages of box-type cookers are linked to the simplicity of the equipment's construction, ease of use, no risk of fires or burns to the operator, and excellent energy capacity, whether reinforced by mirrors or not [60, 71, 77, 84].

Among the indirect heat transfer stoves, the solar panel and parabolic stoves stand out. Solar panel stoves are attractive equipment for travelers or people living alone, and they are easy to construct and do not require expensive materials for assembly. The basic principle of this type of device involves heat transfer to a container intended for cooking food through reflective plates [71]. This device is capable of providing a cooking temperature of around 140 °C, but it is entirely dependent on solar radiation, so it becomes unfeasible for use on cloudy days or at night [55, 77]. Unlike solar panel stoves, parabolic solar stoves stand out as one of the best models of solar stoves for their ability to reach high temperatures. The first models of this device were developed in the 1950s by researcher Ghai in India, who evaluated different ways of obtaining the most efficient parabolic stove. This type of equipment is a concentrator stove, meaning that it is a solar stove in which the pot is placed at the focus of a concentration mirror, so the cooking temperature can reach from 300 to 450 °C [52, 71]. The main disadvantage of this type of equipment is the constant need for sun, the operator's need to monitor the food preparation process to prevent burning, and the risk of fire during the activity [61]. To improve the efficiency of using this type of device, recent research is focused on developing mechanisms that can store energy in parabolic solar ovens to make them viable for use on days with low solar radiation, at night, and for indoor use [6, 31, 67, 69].

The main advantage of using solar cookers is the absence of toxic gas emissions during food preparation. Additionally, these devices can be constructed using a variety of low-cost and highly efficient materials. In a study conducted by [82], different types of waste materials from humanitarian supply packaging were used to develop solar cookers. The authors concluded that the prototypes developed were suitable for domestic use, with those made of cardboard being able to heat food and boil water in relatively short times. Therefore, solar cookers are considered promising technological innovations for replacing biomass-fueled stoves, thereby reducing the emission of gases that affect human health and intensify climate change.

3 Cooking Equipment and Gaseous Emissions: Implications for Climate Change and Human Health

3.1 The Influence of Equipment on Gas Emissions

Around the world, there are approximately 3 billion people who depend on traditional stoves to cook their food, primarily using solid biomass fuels [9]. Given their increasing use, the global research community has begun to shift its focus towards the health impacts associated with emissions during the combustion of fuels in kitchen stoves [9, 93]. Concerns over the type of biomass used are closely related to concerns over exposure to toxic gases that are generated during combustion. However, it is equally important to evaluate the efficiency of the stoves to which this biomass will be used, as more efficient stoves tend to minimize the propagation of smoke.

Both the type of fuel used during cooking and the inefficiency of the stoves used can be harmful to human health, depending on the quantity and types of gases present in the ambient air. A new approach, where the main focus is to advance towards improving these devices to have high combustion efficiency and low emissions, and not to produce any significant pollution, should be given top priority. Stoves containing well-operated chimneys tend to avoid indoor air pollution, however, they will still transfer it to the outside, which could result in substantial human exposure. To truly achieve high performance, more reliable materials should be used in their construction. Advanced ceramics or metal alloys, as well as other components, should be made under good quality control by factories, complemented by other modern production techniques [99].

The search for more advanced and efficient stove designs has been going on for a long time, and it is possible to observe an evolution over the years. To face the challenges related to traditional biomass stoves, scientists have created the concept of improved stoves [8]. However, it was only after the 1980s that parameters such as heat transfer, fluid mechanics, standard testing, etc. were finally taken into consideration to improve stove efficiency [11].

Forced-air biomass stoves, such as those used for cooking and heating, are considered clean technology, containing fans that assist in providing air for the combustion of fuel [17]. They can potentially reduce carbon monoxide (CO) emissions by more than 50% compared to traditional stoves [89, 90]. However, the airflow, distribution, and velocity can directly influence pollutant emissions from incomplete combustion of the biomass used when the O_2 content is not comparable to the combustion rate [24, 25]. For a wood stove, it is recommended that there be two limits and two main zones, the air flow and the mass flow. The air flow can usually be modeled as a limit with known velocity, or the mass flow [57].

Higher temperatures followed by good air conditions can make stoves more efficient, generating lower concentrations of small aerodynamic particles (PM) and carbon monoxide (CO) [47]. This makes the presence of an excess air control system important to avoid excessive unsatisfactory air circulation that can result in higher particle mass concentrations [54].

The open burning of these fuels, on the other hand, can have catastrophic consequences for the environment and human health. This includes the destruction of various ecosystems, increased air pollution, changes in soil properties and consequent increase in erosion, water pollution, and contribution to climate change [63, 80].

3.2 Main Gases Emitted During Food Preparation

The inefficient combustion of wood is a major source of atmospheric pollutants that generate gases such as carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen dioxide (NO_x), and particulate matter less than 2.5 μm (PM2.5), which cause numerous lung diseases [50, 72, 75, 96]. PM is one of the pollutants that poses the greatest risk to human health, in addition to contributing to climate change. PM is a group of solid and liquid particles that are suspended in the atmosphere and have a diameter of less than 2.5 μm [63].

Carbon monoxide is a colorless, odorless, and non-irritating gas that can be fatal in high concentrations, as it binds to hemoglobin in the blood, reducing the amount of oxygen available. It is a product of incomplete combustion of carbon-containing substances [68]. SO_2 is also a colorless gas emitted from fuel combustion. Its formation results from particles containing sulfur and can cause a range of health problems [15]. Nitrogen oxide (NO_x) can act alone or in combination with PM, directly affecting cardiovascular disease. Typically, NO_x is more attributed to motor vehicle emissions [16], but its presence cannot be ruled out when gases from biomass fuel combustion are released.

3.3 Effects of Polluted Gases in Food Preparation on Human Health

Domestic air pollution is generated through the use of inefficient biomass technologies used in cooking or heating. It is estimated that around 3.8 million deaths worldwide are due to indoor air pollution from these technologies, which generate a series of harmful pollutants to human health, including small particles that penetrate the lungs and bloodstream [49]. Intoxication begins with the incomplete burning of the biomass used, emitting pollutants such as carbon monoxide, nitrogen dioxide, sulfur dioxide, among others, as well as volatile organic compounds such as aromatic hydrocarbons and benzene [76]. The particles emitted during burning are captured by the nasal cavity, airways, and thoracic cavity, with smaller particles tending to lodge in areas such as lung alveoli [22].

Organic compounds such as benzene and polycyclic aromatic hydrocarbons are carcinogenic and mutagenic compounds. Prolonged exposure to these pollutants tends to cause cellular alterations in exposed cells, such as those in the nasopharynx, oral cavity, and airways and lungs [28].

Several research studies report that diseases generated by inhaling this smoke occur more frequently in females. There is a disproportionate prevalence of chronic pulmonary diseases and lung cancer, even in those without a history of smoking [56]. This is because in most cases, women are responsible for household tasks, including cooking. Therefore, during the repetitive process of cooking for their family, women would be exposed to emissions generated by biomass fuels for hours, accumulating higher concentrations of these particulates in their bodies. Children who spend more time with their mothers during the cooking process are also diagnosed with these diseases [40].

Intense exposure to household air pollution tends to increase the prevalence of lung diseases, including asthma, tuberculosis, chronic obstructive pulmonary disease

(COPD), interstitial lung disease, acute infections, lung cancer, as well as non-lung diseases such as nasopharyngeal cancer and ischemic heart disease [23, 26, 32, 83]. COPD is a common chronic inflammatory disease characterized by restriction of airflow in the affected person, as well as symptoms associated with the respiratory system. In general, COPD is considered preventable and treatable. On the other hand, its progression can cause respiratory failure, hypertension, pulmonary heart disease, which will seriously affect the patient's quality and life expectancy [104].

In some cases, diseases resulting from excessive exposure to this smoke may come silently, and patients may be asymptomatic or present nonspecific signs such as cough, sputum production, and dyspnea [56]. In these cases, it is recommended that the exposed person undergo periodic examinations to evaluate their condition.

4 Reducing Gas Emissions in Cooking Equipment: Innovative Solutions for a Healthy and Sustainable Future

In recent years, the evaluation of emission reduction strategies for residential biomass combustion has been investigated with growing interest. However, the evaluation of emission factors from biomass combustion is complex due to the dynamics of combustion being influenced by many parameters, such as the technology employed in the stoves, the type of biomass used, and operating conditions. Therefore, strategies can be oriented towards optimizing the combustion process and/or improving the fuel (primary measures), or they can focus on flue gas cleaning technologies (secondary measures).

When the focus is directed towards the use of primary measures in the combustion concept, studies have addressed projects that contemplate the supply of air through the implementation of "staged combustion with air" [18, 43, 62, 108]. In practice, staged combustion with air prioritizes effective mixing of pyrolysis gases and air with a satisfactory residence time. Typically, air supply occurs in two or three stages, depending on the project, with devolatilization of the fuel (primary) and oxidation of the combustion products (secondary and tertiary). Thus, the introduction of heated secondary air at the top of the primary combustion chamber further increases the ignition of the combustion gases.

Regarding energy crops, it is possible to reduce particulate emissions by improving the fuel used. This involves the use of additives such as aluminum silicates (sewage sludge), calcium-based additives (limestone), and sulfur (lignosulfonate) to capture alkaline gas compounds and thus reduce particulate formation [38]. Furthermore, lower emissions can be achieved simply through good stove operating practices. Reference [85] conducted a study on the impact of operator behavior on emissions from manually operated systems. They modified the amount of fuel loaded into the stove and the air flow configuration and found that the operator can have up to six times the influence on particulate emissions from wood-burning stoves. Reference

[101] conducted a study on how operating conditions affect emissions from a wood-burning stove. Two ignition techniques (bottom-up versus top-down), hot start versus cold start, and different fuel loads (low, medium, and high load) were examined. The results indicated that these variables can have a significant impact on emissions. For example, the top-down ignition technique was able to reduce PM10 by more than 50% compared to the traditional bottom-up ignition technique.

Regarding secondary measures, there are several studies on devices that can be applied to combustion gases, controlling pollution in a certain way. Examples include electrostatic precipitators [73, 79, 109], condensation purifiers [41, 79] and catalytic converters [35, 45, 100].

Small-scale electrostatic precipitators (ESPs) are designed to remove inorganic particles present in combustion gases [79]. However, studies report a series of problems, mainly related to the increased toxicity of gases after combustion [48, 100]. This happens because the depollution device can alter the composition of particulate emissions and, as a result, some compounds may become enriched in the combustion gas after the ESP, altering the toxicity of the released particles. In practice, the use of electrostatic precipitators to control PM emissions from small-scale combustion appliances is not economically viable. In addition, their effectiveness is affected by the resistivity of particles, which constantly varies according to the composition of emitted particles [100].

Widely used, including in the residential heating sector, catalytic combustors have a surprising efficiency when it comes to converting polluting gases into non-harmful gases to the environment and human health. Catalytic converters are equipment whose interior has honeycomb-shaped holes composed of precious metals such as platinum, palladium, and rhodium [45]. In the first stage, the gases undergo a reduction, losing oxygen or electrons. In the second stage, the gases undergo an oxidation process. In these processes, gases resulting from incomplete biomass combustion are converted into CO_2, H_2O, and N_2 [45]. A major problem resulting from the use in combustors is related to the low temperature of the combustion gases when using these devices in inefficient combustion appliances. When installed at the beginning of the chimney, temperatures above 500 °C are hardly reached. This is especially problematic during ignition, when emissions can be very high, but the temperature is very low. Another disadvantage is related to the presence of ash, soot, and creosote that encrust on the surface of the catalyst, decreasing its efficiency and requiring constant cleaning of catalytic converters [100].

Condensation purifiers are used in furnaces to reduce emissions of polluting gases into the atmosphere by condensing them, thus removing solid and liquid particles present. In this way, the condensed gases are filtered before being released into the atmosphere. Condensation purifiers are often used in centralized heating systems that use solid fuels such as wood, pellets, or charcoal. Installing a condensation purifier in a furnace requires some modifications to the exhaust system. It is necessary to add a condensation chamber to the system to allow the gases to be cooled and condensed. It is also important to ensure that the condensation purifier has an adequate filtering system to remove all solid and liquid particles present in the combustion gases [35]. Condensation purifiers are a relatively new technology and may be a costly option for many people. However, they are highly efficient in reducing emissions of pollutants and can help improve local air quality and reduce negative impacts on public health. It is important to remember that installing a condensation purifier is not a complete solution to air pollution but rather a part of a larger effort to reduce emissions of pollutants.

Understanding the particulate matter emission factors is crucial for developing effective pollution control strategies. Several studies have shown that detailed analysis of emission factors, considering the technology and fuel type used, can result in large differences in emissions, especially when comparing older residential devices to modern energy conversion technologies, such as automated wood and pellet stoves and highly efficient boilers. While new biomass burning technologies perform much better than traditional systems, their adoption has been gradual. These systems offer significant advantages, such as automatic control, as well as reducing fuel consumption and pollutant emissions. In inefficient manual combustion devices, the main source of particulate matter (PM) is incomplete combustion, which is mainly composed of carbonaceous material, including soot and condensable organic compounds, which have high toxicity and carcinogenic properties [79, 100]. In contrast, properly operated automatic biomass combustion systems mainly emit inorganic salts [100]. Under non-ideal conditions, such as frequently observed in many small-scale combustion devices, the concentration of condensable organic compounds in the combustion gas can be up to 10 times higher than the mass concentration of solid particles collected directly on hot filters in the chimney.

Although there are several options to reduce pollutant formation, secondary strategies for emissions reduction are not well developed for household-scale applications. This is because their installation would increase costs and maintenance, as well as raise safety concerns. Before any implementation in the market, several operational and failure risks still need to be addressed, and test methods for determining removal efficiency need to be standardized and improved. Additionally, recent studies have shown that these reduction technologies can affect the physicochemical characteristics of particulate matter, which can lead to unwanted changes in toxicological responses [48, 100]. For these reasons, it is necessary to study and establish relationships between these alterations and toxicological effects in future research. Under real-life operating conditions, automatic heating appliances have a significantly lower impact on air quality than manually operated stoves. Therefore, it is expected that replacing obsolete technology with modern, high-standard stoves will lead to a substantial reduction in emissions from residential biomass combustion.

5 Advances in Studies on the Use of Combustion Equipment in Food Preparation and Its Environmental Impacts

In order to understand the progress of research over the years on the use of equipment and the environmental and human health impacts of gases released during food preparation around the world, we conducted a bibliometric analysis on the subject and investigated: (i) the number of publications over the years; (ii) countries and institutions that research the most on the topic under analysis; and (iii) keywords as indicative of the most studied topics. The Scopus reference database was used as a data source for bibliometric analysis because it is one of the largest international and multidisciplinary databases of scientific publications [95]. To carry out the survey comprehensively, we used keywords considering the central theme of the present study. Therefore, the following command was employed: (TITLE ("food preparation" OR "food equipment" OR "stove" OR "electric stove" OR "wood burning stove" OR "gas oven" OR "solar ovens") AND TITLE-ABS-KEY ("food safety" OR "food contamination" OR "HPA" OR "climate changes" OR "air pollution" OR "environmental impacts") AND TITLE-ABS-KEY ("biomass" OR "firewood" OR "coal" OR "charcoal" OR "fire" OR "cooking gas")) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "cp") OR LIMIT-TO (DOCTYPE, "ch")). Data collection was carried out in February 2022, and then processed using the "biblioshiny" function in the "bibliometrix" package (ARIA; CUCCURULLO, 2017) of the R Core Team software [81].

307 research studies were found, comprising 268 articles published in scientific journals, 36 conference proceedings, and 3 book chapters, with a total of 1344 authors, including 12 single-authored documents and 1332 multi-authored ones. The first three research articles on the topic analyzed in this survey were published in 1980, and the periods of highest publication intensity were concentrated between the years 2000 and 2022, with 26 documents published in 2017 and 2021, respectively (Fig. 5). This result can be justified by the worldwide interest in seeking measures aimed at reducing environmental impacts caused by gas emissions, including those released during food preparation, which intensify the process of climate change, highlighting the Kyoto Protocol and the Paris Agreement [1].

A total of 57 countries were identified as having conducted research related to the theme under study (Fig. 6). The United States, China, and the United Kingdom are the countries that conduct the most research on gas emissions from food production equipment, with a scientific production frequency of 149, 82, and 27, respectively. These regions are also where the main institutes that conduct research on this theme are located, with the University of California (49 published articles), Tsinghua University (24 published articles), Colorado State University (19 published articles), and Peking University (14 published articles) standing out. The interest of these countries in conducting research on this topic is entirely linked to the fact that both countries are among the world's largest economic powers and, consequently, the largest greenhouse gas (GHG) emitters, accelerating the process of climate change

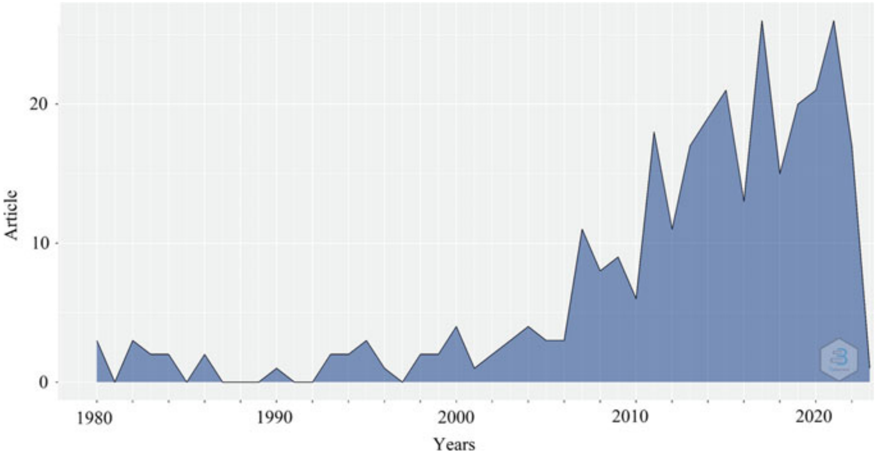

Fig. 5 Scientific production over the years (*Source* The authors 2023)

[2]. However, the countries responsible for the largest release of gases from the burning of biomass in food preparation are classified as poor or developing countries [22]. Nonetheless, they are the ones that least seek measures to minimize the environmental and human health impacts resulting from this practice, as evidenced in this research survey.

A total of 754 keywords were identified by the authors for indexing the articles in databases, with the most frequent terms being indoor air pollution (n = 42), biomass (n = 35), household air pollution (n = 33), particulate matter (n = 28), carbon monoxide (n = 16), cookstove (n = 12), and China (n = 11). Keywords serve to indicate the thematic studies within a research niche [98]. Figure 7 shows the most commonly used keywords over a temporal scale, with recent studies focused

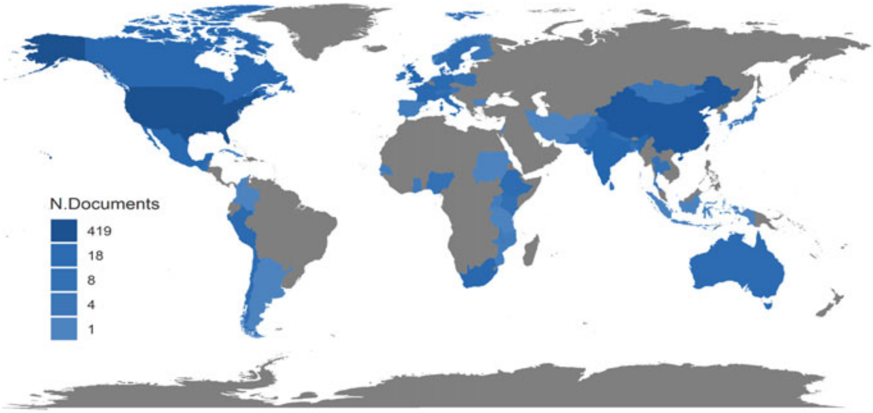

Fig. 6 Scientific production of the countries (*Source* The authors 2023)

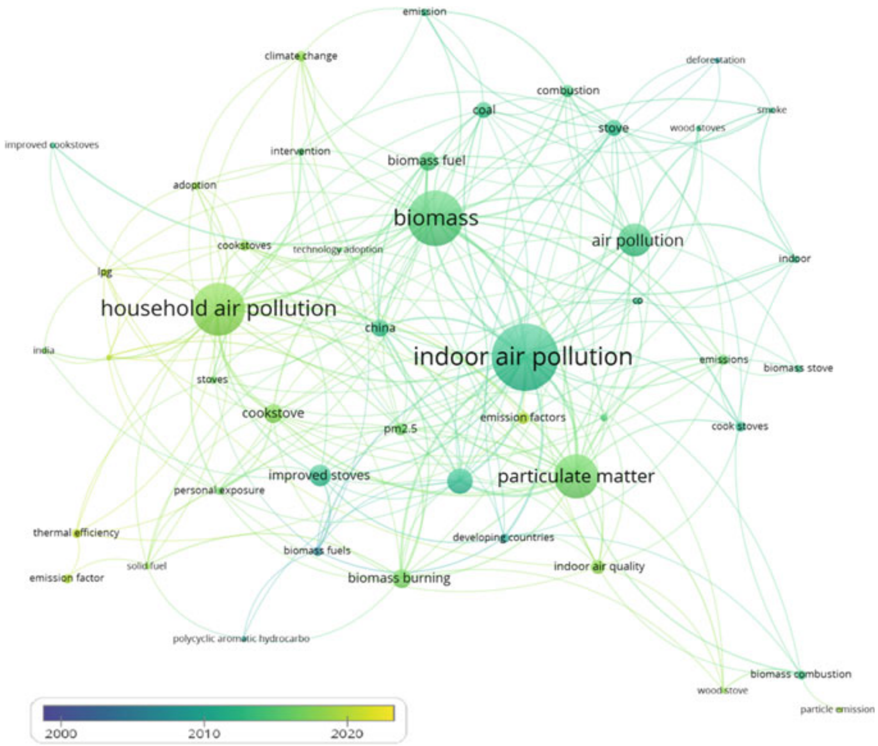

Fig. 7 Network of interactions between keywords over time (*Source* The authors 2023)

on researching the impacts and seeking solutions to air pollution in domestic environments and the particulate matter released during biomass burning for food preparation. This result highlights the global concern to find new cooking equipment that is less harmful to the environment and human health.

6 Conclusions

Throughout history, biomass-fueled cooking equipment such as ovens, stoves, grills, and many others have been widely used worldwide, from the oldest to the most modern ones. These devices are essential for food preparation in many cultures. However, the use of these devices has a significant impact on gas emissions and climate change because the gases emitted during the burning of wood and biomass contribute to air pollution and global warming. The main gases emitted are carbon dioxide (CO_2), carbon monoxide (CO), and particulate matter (PM), which can cause respiratory and cardiovascular problems in humans. To mitigate these gas emissions, many efforts have been made to develop more efficient technologies for biomass and wood-fired cooking equipment, such as stoves and ovens with more efficient and ventilated burners. Additionally, the use of alternative fuels such as biomass briquettes and pellets has also been explored.

Although there are challenges in mitigating gas emissions from these equipment, technology is advancing rapidly and many innovations have been developed to make them more efficient and less polluting. The use of these equipment is part of the culture and tradition of many people, and the search for solutions to make them more sustainable is important to ensure the safety and health of human beings and the environment.

From the bibliometric review, it is also evident the need for further studies aimed at the development of new equipment for more sustainable and less harmful food preparation, especially in countries where biomass is the main source of energy for cooking. Investment in research in this area will provide improvement in the quality of life of the world's population and reduce the environmental impacts caused by greenhouse gas (GHG) emissions.

References

1. Abbass K, Qasim MZ, Song H, Murshed M, Mahmood H, Younis I (2022) A review of the global climate change impacts, adaptation, and sustainable mitigation measures. Environ Sci Pollut Res 29(28):42539–42559. https://doi.org/10.1007/s11356-022-19718-6
2. Althor G, Watson JEM, Fuller RA (2016) Global mismatch between greenhouse gas emissions and the burden of climate change. Sci Rep 6(1):20281. https://doi.org/10.1038/srep20281
3. Anhalt J, Holanda S (2009) Implementation of a dissemination strategy for efficient cook stoves in Northeast Brazil (10604030):29
4. Arunachala UC, Kundapur A (2020) Cost-effective solar cookers: a global review. Sol Energy 207:903–916. https://doi.org/10.1016/j.solener.2020.07.026
5. Rahman ML (2010) Improved Cooking Stoves in South Asia. SAARC Energy Centre, Islamabad, Pakistan
6. Asmelash H, Bayray M, Kimambo C, Gebray P, Sebbit A (2014) Performance test of parabolic trough solar cooker for indoor cooking. Momona Ethiopian J Sci 6(2):39. https://doi.org/10.4314/mejs.v6i2.109621
7. Bailis R, Cowan A, Berrueta V, Masera O (2009) Arresting the killer in the kitchen: the promises and pitfalls of commercializing improved cookstoves. World Dev 37(10):1694–1705
8. Bank W (2011) Problems and opportunities. Cogeneration Distrib Gener J 26(1):5–6. https://doi.org/10.4324/9780203360835_chapter_11
9. Bargman JM, Breborowicz A, Rodela H, Abraham G, Oreopoulos DG (1988) Absorption of recombinant human erythropoietin (EPO) from the peritoneal-cavity in rabbits. In: Kidney international. Blackwell Science Inc., 350 Main St., Malden, MA 02148, p 243
10. Barnes DF, Openshaw K, Smith KR, van der Plas R (1994) What makes people cook with improved biomass stoves. World Bank technical paper 242:2004
11. Berry J, Anstey N, Spillane N, Birzer C (2019) Design for mass production and dissemination of clean cookstoves in developing countries. World Engineers Convention (October):628–646
12. Black D (1932) Evidences of the use of fire by Sinanthropus. Bull Geol Soc China 11:107–108
13. Blunck M, Griebenow C, Rammelt M, Zimm C (2011) Carbon markets for improved cooking stoves: a GIZ guide for project operators. GIZHERA—poverty-oriented Basic Energy Services, Eschborn, Germany
14. Bronowski J (1973) The ascent of man little brown and company

15. Brook RD, Franklin B, Cascio W, Hong Y, Howard G, Lipsett M, Luepker R, Mittleman M, Samet J, Smith SC, Tager I (2004) Air pollution and cardiovascular disease: a statement for healthcare professionals from the expert panel on population and prevention science of the American Heart Association. Circulation 109(21):2655–2671. https://doi.org/10.1161/01.CIR.0000128587.30041.C8
16. Brook RD, Rajagopalan S, Pope CA, Brook JR, Bhatnagar A, Diez-Roux AV, Holguin F, Hong Y, Luepker RV, Mittleman MA, Peters A, Siscovick D, Smith SC, Whitsel L, Kaufman JD (2010) Particulate matter air pollution and cardiovascular disease: an update to the scientific statement from the American heart association. Circulation 121(21):2331–2378. https://doi.org/10.1161/CIR.0b013e3181dbece1
17. Carter EM, Shan M, Yang X, Li J, Baumgartner J (2014) Pollutant emissions and energy efficiency of Chinese gasifier cooking stoves and implications for future intervention studies. Environ Sci Technol 48(11):6461–6467. https://doi.org/10.1021/es405723w
18. Choi M, Kim K, Li X, Deng K, Park Y, Seo M, Sung Y, Choi G (2020) Strategic combustion technology with exhaust tube vortex flame: combined effect of biomass co-firing and air-staged combustion on combustion characteristics and ash deposition. Energy 203:117839. https://doi.org/10.1016/J.ENERGY.2020.117839
19. Crewe E (1997) The silent tradition of development cooks. In: Discourses of development: anthropological perspective, pp 59–80
20. Cuce E, Cuce PM (2013) A comprehensive review on solar cookers. Appl Energy 102:1399–1421. https://doi.org/10.1016/j.apenergy.2012.09.002
21. Cuce PM (2018) Box type solar cookers with sensible thermal energy storage medium: a comparative experimental investigation and thermodynamic analysis. Sol Energy 166:432–440. https://doi.org/10.1016/j.solener.2018.03.077
22. Cupertino GFM, Souza EC de, Souza Júnior AD de, Delatorre FM, Santos Júnior AJ dos, da Silva ÁM, Pereira AKS, Mesquita JG, Ucella Filho JGM, Oliveira TR, Cezário LFC, de Oliveira MP, Curty TA, Dias Júnior AF (2022) Biomass use and exposure to residential air pollution increase the risk of servere COVID-19. In: Biomassa: recursos, aplicações e tecnologias em pesquisas. Editora Científica Digital, pp 33–47
23. Dean Hosgood H, Boffetta P, Greenland S, Lee YCA, Mclaughlin J, Seow A, Duell EJ, Andrew AS, Zaridze D, Szeszenia-Dabrowska N, Rudnai P, Lissowska J, Fabiánová E, Mates D, Bencko V, Foretova L, Janout V, Morgenstern H, Rothman N, Hung RJ, Brennan P, Lan Q (2010) In-home coal and wood use and lung cancer risk: a pooled analysis of the international lung cancer consortium. Environ Health Perspect 118(12):1743–1747. https://doi.org/10.1289/ehp.1002217
24. Deng M, Li P, Shan M, Yang X (2020) Optimizing supply airflow and its distribution between primary and secondary air in a forced-draft biomass pellet stove. Environ Res 184(July 2019):109301. https://doi.org/10.1016/j.envres.2020.109301
25. Deng M, Nie Y, Yuan Y, Ma R, Shan M, Yang X (2022) The impact of oxygen content in the primary air supply on fuel burning rate and pollutant emissions in a forced-draft biomass stove. Fuel 321(x):124129. https://doi.org/10.1016/j.fuel.2022.124129
26. Dennis RJ, Maldonado D, Norman S, Baena E, Martinez G (1996) Woodsmoke exposure and risk for obstructive airways disease among women. Chest 109(1):115–119. https://doi.org/10.1378/chest.109.1.115
27. Devan PK, Bibin C, Gowtham S, Hariharan G, Hariharan R (2020) A comprehensive review on solar cooker with sun tracking system. Mater Today Proc 33:771–777. https://doi.org/10.1016/j.matpr.2020.06.124
28. Dutta A, Ray MR (2014) Hypertension and respiratory health in biomass smoke-exposed premenopausal Indian women. Air Qual Atmos Health 7(2):229–238. https://doi.org/10.1007/s11869-013-0228-5
29. Eckholm E (1975) The other energy crisis: firewood. Worldwatch paper
30. Eckholm E, Foley G, Barnard G, Timberlake L (1984) Fuelwood: the energy crisis that won't go away. Earthscan

31. El Moussaoui N, Talbi S, Atmane I, Kassmi K, Schwarzer K, Chayeb H, Bachiri N (2020) Feasibility of a new design of a Parabolic Trough Solar Thermal Cooker (PSTC). Sol Energy 201:866–871. https://doi.org/10.1016/j.solener.2020.03.079
32. Epton MJ, Dawson RD, Brooks WM, Kingham S, Aberkane T, Cavanagh JAE, Frampton CM, Hewitt T, Cook JM, McLeod S, McCartin F, Trought K, Brown L (2008) The effect of ambient air pollution on respiratory health of school children: a panel study. Environ Health 7:1–11. https://doi.org/10.1186/1476-069X-7-16
33. Erarslan A (2021) A traditional wooden corbelled dome construction technique from Anatolia. The Eastern Anatolian Tandoor house with its wooden "swallow-dome" type of roof 21(4):1275–1303. https://doi.org/10.1080/13467581.2021.1929243, https://doi.org/10.1080/13467581.2021.1929243
34. Ezzati M, Bailis R, Kammen DM, Holloway T, Price L, Cifuentes LA, Barnes B, Chaurey A, Dhanapala KN (2004) Energy management and global health* 29:383–419. https://doi.org/10.1146/annurev.energy29062103121246, https://doi.org/10.1146/ANNUREV.ENERGY.29.062103.121246
35. Feng Y, Li Y, Cui L, Yan L, Zhao C, Dong Y (2019) Cold condensing scrubbing method for fine particle reduction from saturated flue gas. Energy 171:1193–1205. https://doi.org/10.1016/J.ENERGY.2019.01.065
36. Foley G, Moss P, Timberlake L (1984) Stoves and trees: how much wood would a woodstove save if a woodstove could save wood? Earthscan
37. Foster C (2007) Rocket Lorena Stove—Appropedia. License CC-BY-SA-4.0. https://www.appropedia.org/Rocket_Lorena_Stove. Accessed 3 May 2023
38. Fournel S, Palacios JH, Godbout S, Heitz M (2015) Effect of additives and fuel blending on emissions and ash-related problems from small-scale combustion of reed canary grass. Agriculture 5(3):561–576. https://doi.org/10.3390/AGRICULTURE5030561
39. Gill J (1987) Improved stoves in developing countries: a critique. Energy Policy 15(2):135–144
40. Gogoi D, Sazid A, Bora J, Deka P, Balachandran S, Hoque RR (2021) Particulate matter exposure in biomass-burning homes of different communities of Brahmaputra Valley. Environ Monit Assess 193(12). https://doi.org/10.1007/s10661-021-09624-8
41. Grigonyte J, Nuutinen I, Koponen T, Lamberg H, Tissari J, Jokiniemi J, Sippula O (2014) Evaluation of a heat exchanger designed for efficient fine particle precipitation in small-scale wood combustion. Energy Fuels 28(9):6058–6065. https://doi.org/10.1021/EF500958X/ASSET/IMAGES/LARGE/EF-2014-00958X_0006.JPEG
42. Hanbar RD, Karve P (2002) National Programme on Improved Chulha (NPIC) of the Government of India: an overview. Energy Sustain Dev 6(2):49–55. https://doi.org/10.1016/S0973-0826(08)60313-0
43. He Z, Liu S, Wang S, Liu W, Li Y, Feng X (2022) Reduced pollutant emissions and slagging rate of biomass pellet combustion by optimizing the multilayer distribution of secondary air. ACS Omega 7(33):28962–28973. https://doi.org/10.1021/ACSOMEGA.2C02587/ASSET/IMAGES/MEDIUM/AO2C02587_M011.GIF
44. Herez A, Ramadan M, Khaled M (2018) Review on solar cooker systems: economic and environmental study for different Lebanese scenarios. Renew Sustain Energy Rev 81:421–432. https://doi.org/10.1016/j.rser.2017.08.021
45. Hukkanen A, Kaivosoja T, Sippula O, Nuutinen K, Jokiniemi J, Tissari J (2012) Reduction of gaseous and particulate emissions from small-scale wood combustion with a catalytic combustor. Atmos Environ 50:16–23. https://doi.org/10.1016/J.ATMOSENV.2012.01.016
46. Jassim MM, Abbood MH, Rashid FL (2022) Design and construction solar oven sterilizer. Int J Heat Technol 40(2):641–645. https://doi.org/10.18280/ijht.400235
47. Johansson LS, Leckner B, Gustavsson L, Cooper D, Tullin C, Potter A (2004) Emission characteristics of modern and old-type residential boilers fired with wood logs and wood pellets. Atmos Environ 38(25):4183–4195. https://doi.org/10.1016/j.atmosenv.2004.04.020
48. Kaivosoja T, Jalava PI, Lamberg H, Virén A, Tapanainen M, Torvela T, Tapper U, Sippula O, Tissari J, Hillamo R, Hirvonen MR, Jokiniemi J (2013) Comparison of emissions and

toxicological properties of fine particles from wood and oil boilers in small (20–25 kW) and medium (5–10 MW) scale. Atmos Environ 77:193–201. https://doi.org/10.1016/J.ATMOSENV.2013.05.014

49. Kansiime WK, Mugambe RK, Atusingwize E, Wafula ST, Nsereko V, Ssekamatte T, Nalugya A, Coker ES, Ssempebwa JC, Isunju JB (2022) Use of biomass fuels predicts indoor particulate matter and carbon monoxide concentrations; evidence from an informal urban settlement in Fort Portal city, Uganda. BMC Public Health 22(1):1–12. https://doi.org/10.1186/s12889-022-14015-w
50. Karanasiou A, Alastuey A, Amato F, Renzi M, Stafoggia M, Tobias A, Reche C, Forastiere F, Gumy S, Mudu P, Querol X (2021) Short-term health effects from outdoor exposure to biomass burning emissions: a review. Sci Total Environ 781:146739. https://doi.org/10.1016/j.scitotenv.2021.146739
51. Kaur-Sidhu M, Ravindra K, Mor S, John S (2020) Emission factors and global warming potential of various solid biomass fuel-cook stove combinations. Atmos Pollut Res 11(2):252–260. https://doi.org/10.1016/J.APR.2019.10.009
52. Kedar SA, Sonawale P, Valve P, Khujat P, Talekar P (2017) Thermal analysis of parabolic solar cooker with back reflection. Mater Today Proc 4(8):8035–8039. https://doi.org/10.1016/j.matpr.2017.07.141
53. Khadilkar P (2017) Formulation of a Framework for needs analysis and Stakeholders' behavioral Simulation for design for the Bop
54. Khodaei H, Guzzomi F, Patiño D, Rashidian B, Yeoh GH (2017) Air staging strategies in biomass combustion-gaseous and particulate emission reduction potentials. Fuel Process Technol 157:29–41. https://doi.org/10.1016/j.fuproc.2016.11.007
55. Kimambo CZM (2007) Development and performance testing of solar cookers. J Energy Southern Africa 18(3):41–51. https://doi.org/10.17159/2413-3051/2007/v18i3a3384
56. Koo CW, Gupta N, Baliff JP, Hudock K, Haas AR (2011) A tale of two sisters: biomass fuel exposure-related lung disease. Clin Radiol 66(2):190–193. https://doi.org/10.1016/j.crad.2010.08.006
57. Koraïem M, Assanis D (2021) Wood stove combustion modeling and simulation: technical review and recommendations. Int Commun Heat Mass Transfer 127(August):105423. https://doi.org/10.1016/j.icheatmasstransfer.2021.105423
58. Kristoferson LA, Bokalders V (1986) Wood and charcoal stoves. Renew Energy Technol 68–87. https://doi.org/10.1016/B978-0-08-034061-6.50013-5
59. Kshirsagar MP, Kalamkar VR (2014) A comprehensive review on biomass cookstoves and a systematic approach for modern cookstove design. Renew Sustain Energy Rev 30:580–603. https://doi.org/10.1016/j.rser.2013.10.039
60. Kumar S (2004) Natural convective heat transfer in trapezoidal enclosure of box-type solar cooker. Renew Energy 29(2):211–222. https://doi.org/10.1016/S0960-1481(03)00193-9
61. Lentswe K, Mawire A, Owusu P, Shobo A (2021) A review of parabolic solar cookers with thermal energy storage. Heliyon 7(10):e08226. https://doi.org/10.1016/j.heliyon.2021.e08226
62. Li PW, Chyang CS (2020) A comprehensive study on NO_x emission and fuel nitrogen conversion of solid biomass in bubbling fluidized beds under staged combustion. J Energy Inst 93(1):324–334. https://doi.org/10.1016/J.JOEI.2019.02.007
63. Lima FDM, Pérez-Martínez PJ, de Fatima AM, Kumar P, de Miranda RM (2020) Characterization of particles emitted by pizzerias burning wood and briquettes: a case study at Sao Paulo, Brazil. Environ Sci Pollut Res 27(29):35875–35888. https://doi.org/10.1007/s11356-019-07508-6
64. MacCarty N, Ogle D, Still D, Bond T, Roden C (2008) A laboratory comparison of the global warming impact of five major types of biomass cooking stoves. Energy Sustain Dev 12(2):56–65. https://doi.org/10.1016/S0973-0826(08)60429-9
65. Mannan M (1996) Women targeted and women negated. Dev Pract 6(2):113–120
66. Manjo Kumar, Sachin Kumar, Tyagi SK (2013) Design, development and technological advancement in the biomass cookstoves: a review. Renew Sustain Energy Rev 26:265–285. https://doi.org/10.1016/j.rser.2013.05.010

67. Mbodji N, Hajji A (2017) Modeling, testing, and parametric analysis of a parabolic solar cooking system with heat storage for indoor cooking. Energy Sustain Soc 7(1):32. https://doi.org/10.1186/s13705-017-0134-z
68. Miah MD, Al Rashid H, Shin MY (2009) Wood fuel use in the traditional cooking stoves in the rural floodplain areas of Bangladesh: a socio-environmental perspective. Biomass Bioenergy 33(1):70–78. https://doi.org/10.1016/j.biombioe.2008.04.015
69. Mishra A, Powar S, Dhar A (2019) Solar thermal powered bakery oven, pp 577–592
70. MNRE (2010) National Biomass Cookstoves Programme (NBCP). Special Project on Cookstove (SPC)
71. Muthusivagami RM, Velraj R, Sethumadhavan R (2010) Solar cookers with and without thermal storage—a review. Renew Sustain Energy Rev 14(2):691–701. https://doi.org/10.1016/j.rser.2008.08.018
72. Naeher LP, Brauer M, Lipsett M, Zelikoff JT, Simpson CD, Koenig JQ, Smith KR (2007) Woodsmoke health effects: a review. Inhal Toxicol 19(1):67–106. https://doi.org/10.1080/08958370600985875
73. Oischinger J, Steiner M, Meiller M, Hebauer M, Beer S, Daschner R, Hornung A, Kramb J (2020) Optimization of the fractional collection efficiencies for electrostatic precipitators used in biomass-fired boilers. Biomass Bioenergy 141:105703. https://doi.org/10.1016/J.BIOMBIOE.2020.105703
74. Omara AAM, Abuelnuor AAA, Mohammed HA, Habibi D, Younis O (2020) Improving solar cooker performance using phase change materials: a comprehensive review. Sol Energy 207:539–563. https://doi.org/10.1016/j.solener.2020.07.015
75. Ozgen S, Caserini S, Galante S, Giugliano M, Angelino E, Marongiu A, Hugony F, Migliavacca G, Morreale C (2014) Emission factors from small scale appliances burning wood and pellets. Atmos Environ 94:144–153. https://doi.org/10.1016/j.atmosenv.2014.05.032
76. Padma TV (2007) Biomass fuels blamed for premature deaths in rural settings. Nat Med 13(2):112. https://doi.org/10.1038/nm0207-112a
77. Pandey S, Goswami S, Saini P, Powar S, Dhar A (2021) Hybrid electrical-solar oven: a new perspective pp 237–255
78. Pei WC (1934) A preliminary report on the late-Palæolithic cave of Choukoutien 1. Bull Geol Soc China 13(1):327–358
79. Pham M, Pakrasi A (2019) Air pollution control technologies. In: Proceedings of the air and waste management association's annual conference and exhibition, AWMA, pp 377–428. https://doi.org/10.1016/B978-0-12-814934-8.00013-2
80. Pivello VR, Vieira I, Christianini AV, Ribeiro DB, da Silva ML, Berlinck CN, Melo FPL, Marengo JA, Tornquist CG, Tomas WM, Overbeck GE (2021) Understanding Brazil's catastrophic fires: causes, consequences and policy needed to prevent future tragedies. Perspect Ecol Conserv 19(3):233–255. https://doi.org/10.1016/j.pecon.2021.06.005
81. R Core Team K (2021) R: A language and environment for statistical computing
82. Regattieri A, Piana F, Bortolini M, Gamberi M, Ferrari E (2016) Innovative portable solar cooker using the packaging waste of humanitarian supplies. Renew Sustain Energy Rev 57:319–326. https://doi.org/10.1016/j.rser.2015.12.199
83. Sandoval J, Salas J, Martinez-Guerra ML, Gomez A, Martinez C, Portales A, Palomar A, Villegas M, Barrios R (1993) Pulmonary arterial hypertension and cor pulmonale associated with chronic domestic woodsmoke inhalation. Chest 103(1):12–20. https://doi.org/10.1378/chest.103.1.12
84. Saxena A, Varun PSP, Srivastav G (2011) A thermodynamic review on solar box type cookers. Renew Sustain Energy Rev 15(6):3301–3318. https://doi.org/10.1016/j.rser.2011.04.017
85. Schmidl C, Luisser M, Padouvas E, Lasselsberger L, Rzaca M, Ramirez-Santa Cruz C, Handler M, Peng G, Bauer H, Puxbaum H (2011) Particulate and gaseous emissions from manually and automatically fired small scale combustion systems. Atmos Environ 45(39):7443–7454. https://doi.org/10.1016/J.ATMOSENV.2011.05.006
86. SCI SCI (2023) Solar cookers international. https://www.solarcookers.org/about

87. Sedighi M, Salarian H (2017) A comprehensive review of technical aspects of biomass cookstoves. Renew Sustain Energy Rev 70:656–665
88. Sesan TA (2011) What's cooking? Participatory and market approaches to stove development in Nigeria and Kenya. Technol Soc 39(July):142–150
89. Shan M, Carter E, Baumgartner J, Deng M, Clark S, Schauer JJ, Ezzati M, Li J, Fu Y, Yang X (2017) A user-centered, iterative engineering approach for advanced biomass cookstove design and development. Environ Res Lett 12(9). https://doi.org/10.1088/1748-9326/aa804f
90. Shen G, Tao S, Wei S, Zhang Y, Wang R, Wang B, Li W, Shen H, Huang Y, Chen Y, Chen H, Yang Y, Wang W, Wei W, Wang X, Liu W, Wang X, Simonich SLM (2012) Reductions in emissions of carbonaceous particulate matter and polycyclic aromatic hydrocarbons from combustion of biomass pellets in comparison with raw fuel burning. Environ Sci Technol 46(11):6409–6416. https://doi.org/10.1021/es300369d
91. Smith KR (1989) Dialectics of improved stoves. Econ Polit Wkly 517–522
92. Smith KR, Mehta S, Maeusezahl-Feuz M (2004) Indoor air pollution from household use of solid fuels. In: Comparative quantification of health risks: global and regional burden of disease attributable to selected major risk factors, vol 2, pp 1435–1493
93. Smith KR, Samet JM, Romieu I, Bruce N (2000) Indoor air pollution in developing countries and acute lower respiratory infections in children. Thorax 55(6):518–532. https://doi.org/10.1136/thorax.55.6.518
94. Sulilatu WF (1984) Danger signals to human health
95. Sweileh WM (2018) Research trends on human trafficking: a bibliometric analysis using Scopus database. Global Health 14(1):106. https://doi.org/10.1186/s12992-018-0427-9
96. Taner S, Pekey B, Pekey H (2013) Fine particulate matter in the indoor air of barbeque restaurants: elemental compositions, sources and health risks. Sci Total Environ 454–455:79–87. https://doi.org/10.1016/j.scitotenv.2013.03.018
97. Troncoso K, Castillo A, Masera O, Merino L (2007) Social perceptions about a technological innovation for fuelwood cooking: case study in rural Mexico. Energy Policy 35(5):2799–2810
98. Ucella-Filho JGM, da Freire ASM, Carréra JC, Lucas FMF, Zucolotto SM, Dias Júnior AF, Mori FA (2022) Tannin-rich bark extract of plants as a source of antimicrobial bioactive compounds: a bibliometric analysis. South Afr J Botany 150:1038–1050. https://doi.org/10.1016/j.sajb.2022.09.018
99. Venkataraman C, Sagar AD, Habib G, Lam N, Smith KR (2010) The Indian national initiative for advanced biomass cookstoves: the benefits of clean combustion. Energy Sustain Dev 14(2):63–72. https://doi.org/10.1016/j.esd.2010.04.005
100. Vicente ED, Alves CA (2018) An overview of particulate emissions from residential biomass combustion. Atmos Res 199:159–185. https://doi.org/10.1016/J.ATMOSRES.2017.08.027
101. Vicente ED, Duarte MA, Calvo AI, Nunes TF, Tarelho L, Alves CA (2015) Emission of carbon monoxide, total hydrocarbons and particulate matter during wood combustion in a stove operating under distinct conditions. Fuel Process Technol 131:182–192. https://doi.org/10.1016/J.FUPROC.2014.11.021
102. Westhoff B, Germann D (1995) Stove images: a documentation of improved and traditional stoves in Africa, Asia and Latin America
103. Wu J, Cheng F, Zhang D (2021) Health effect of indoor $Pm_{2.5}$ and co emissions from coal and biomass fired domestic appliances in remote rural China. Int J Energy Clean Environ 22(5):33–49. https://doi.org/10.1615/INTERJENERCLEANENV.2021036424
104. Wu J, Zhao X, Xiao C, Xiong G, Ye X, Li L, Fang Y, Chen H, Yang W, Du X (2022) The role of lung macrophages in chronic obstructive pulmonary disease. Respir Med 205(August):107035. https://doi.org/10.1016/j.rmed.2022.107035
105. Xiangjum Y (1993) Chinese fuel saving stoves: a compendium
106. Xiliang Z, Smith KR (2005) Programmes promoting improved household stoves in China. Boiling Point 50:14–16
107. Yettou F, Azoui B, Malek A, Gama A, Panwar NL (2014) Solar cooker realizations in actual use: an overview. Renew Sustain Energy Rev 37:288–306. https://doi.org/10.1016/j.rser.2014.05.018

108. Zadravec T, Rajh B, Kokalj F, Samec N (2020) CFD modelling of air staged combustion in a wood pellet boiler using the coupled modelling approach. Therm Sci Eng Prog 20:100715. https://doi.org/10.1016/J.TSEP.2020.100715
109. Zhang R, Xu G, Li B, Wang Z, Gao J, Li J, Sun Y, Xu G (2023) Analysis of the pollution emission system of large-scale combustion of biomass briquette fuel in China. Process Saf Environ Prot 169:928–936. https://doi.org/10.1016/J.PSEP.2022.11.088

Wastes from Sustainable Forest Management as a Source of Biomass: The Case of Amazonia for Bioenergy Generation

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Abstract Knowledge about the availability and application of Amazonian wood wastes from sustainable forest management plans (SFMP) in energy generation is essential when considering a third of the world's population depends on wood as an energy source. In tropical countries such as Brazil, technological initiatives may be combined with scientific studies to add value to forest biomass and enhance its use as an energy input in the Legal Amazonia. The integral conversion of dense tropical forest vegetation to charcoal or supplying thermoelectric plants would not be admissible; however, forest wastes are sustainable and promising alternatives. This chapter aims to present: (i) the energy potential of wood wastes from SFMP in Amazonia and its importance in the sustainable expansion of energy systems and (ii) the potential of wood wastes to replace non-renewable sources, such as fossil fuels, to reduce the logging of tropical forests for energy generation. The biggest challenges

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to producing sustainable energy from forest wastes in Amazonia are related to the low technological level of the kilns used to produce charcoal and the high variation in the wood characteristics concerning its dimensions and its physical, chemical, and energy properties. In that chapter, it was demonstrated that the diameter of the wastes varies from 0.123 to 0.760 m, and the basic density, for example, varies from 0.221 to 0.935 g/cm^3 between species. Studies were carried out to characterize these residual woods and solve these problems. This characterization promoted scientific development. The segregation of wastes according to their properties, mainly the basic density, increased the productivity of the kilns and the quality of the charcoal derived. Future research will address technological improvements in energy production through SFMP wastes to increase efficiency, quality, and sustainability.

Keywords Renewable energy · Wood quality · Residual biomass · Carajás pole · Bioreducer

1 Introduction

Using wood wastes from SFMP as fuel is a sustainable alternative for diversifying the national and even global energy matrix. In Amazonia, these lignocellulosic wastes are formed mainly by branches, buttresses, and stumps of felled trees, usually of large dimensions. Such wastes can represent up to two-thirds of the dry mass of the tree [29]. Therefore, they are highly available and economically viable. In addition, waste consumption is heading towards maximum efficiency in using natural resources.

Some studies have discussed interesting aspects of the environmental impact of extracting wastes from SFMP worldwide [1, 25] and found no negative effect on tree growth. On the contrary, they indicated positive effects of stump extraction on forest regeneration [25, 28]. Based on published data worldwide, the literature indicates that waste extraction increases nutrient export [1]. The export effect is complex because it is affected by the harvest cycle and specific characteristics of the logged forest ecosystem, such as the input of nutrients by weathering and output by leaching [32, 44]. Compared to fossil fuels, burning wood and charcoal emits low amounts of greenhouse gases [11]. The carbon emitted will be stored again during forest regeneration [9] promoted by techniques associated with SFMP [28].

Carbonization is an important conversion route for using by-products from forest management. In addition to its wide domestic use, charcoal is used in blast furnaces of steel mills as a biothermoreducer for pig iron, in the production of the called "green steel." The Carajás region, located in eastern Amazonia, has the largest pig iron production in northern Brazil [41]. Forest wastes partially supply the region's firewood demand for charcoal production [24].

The great challenge for the energy use of wastes from SFMP refers to the high variability of their characteristics. Lima et al. [19] found variation in the wood basic density from 0.525 to 0.895 g/cm^3. In addition, the wood presents high moisture, representing up to 45% of the wet mass without bark [24]. Basic density and moisture influence the productivity of the kilns [4]. This variability is increased by the lack of carbonization control [39] commonly carried out in brick kilns of low technologic level known as "hot tail." The carbonization in these handmade kilns is controlled empirically, without temperature control or waste separation into quality classes.

Studies have been carried out to understand the variation in the quality of charcoal derived from waste [19, 23]. In general, the separation of wastes into groups of species according to the different wood characteristics significantly improves the productivity of the kilns, increases the yield, and reduces the variation in the charcoal quality compared to the conventional method [5]. The next steps involve conducting research that will contribute to more effective control of carbonization, increase its yield, improve the quality of charcoal derived from forest wastes in Amazonia, and mitigate gas emissions during carbonization. This chapter aims to describe the advances obtained so far related to the energy use of forest wastes arising from SFMP in Amazonia.

2 Background of Studies with Wastes from SFMP

The project entitled "Valuation of wood wastes from sustainable forest management for bioenergy in Legal Amazonia" (Public Selection Notice for Scientific and Technological Research—Edition 2018) was developed by the Federal Rural University of Amazonia (website: https://novo.ufra.edu.br/) and financed directly by the Banco da Amazônia. Several advances were achieved in understanding the characteristics of primary wastes from SFMP in Amazonia. It was possible to understand the variability of the main physical, chemical, and energy properties of the forest biomass used for bioenergy in Amazonia [19, 23]. Consequently, the data collected will allow decision-making in industrial units, such as steel mills and ceramics.

The various studies analyzed the wood characteristics of species from 22 genera. The waste characteristics that varied the most were basic density (0.525–0.895 g/cm^3), ash content (0.3–2.5%), and total extractives (1.7–17.9%). However, the elemental carbon content (49.18–52.16%), total lignin (30.2–38.1%), fixed carbon (16.5–22.0%), volatile matter (76.7–82. 8%), and higher heating value (19.4–20.4 MJ/kg) were characteristics that showed the smallest variations between the studied species [19]. Within the same species, wood properties have smaller ranges of variation. In the study of Lima et al. [19], *Manilkara elata* and *Dinizia excelsa* had a basic density of 0.900 and 0.890 g/cm^3, respectively. On the other hand, Lima et al. [24] reported values of 0.872 and 0.927 g/cm^3 of basic density for the same species. Between the two studies, there was a difference of about 3%. This variation can be considered low since this residual biomass has no genetic, age, or site control. These findings indicate the reliability and possibility of data extrapolation to represent the overall quality of waste from these species.

Based on the physical, chemical, and energy characterization of the wastes, it was demonstrated that the wood of the species has the quality to generate electric energy in boilers [19] and in charcoal production for domestic and industrial use. Lima et al. [19] verified a species effect on the technological properties of residual woods, making it necessary to qualify them for energy production. The use of wood wastes with up to 30% moisture (wet basis) has proven to be viable in modern cogeneration systems.

The species studied, such as *D. excelsa*, *M. elata*, *P. altissium,* and *G. glabra*, showed better energy properties than species and clones traditionally used in energy forests. *D. excelsa* had the highest mass of CO_2eq fixed in 1 m^3 of wood wastes (1687 kg), meaning that the use of 1 m^3 of wood wastes of this species would mitigate the emission of 1687 kg of CO_2eq. Finally, the wastes of this species showed the best properties for bioenergy.

The second step of the project proposed waste segregation for charcoal production. Principal component analysis (PCA), a multivariate statistical technique, enabled forming species groups with similar properties [19, 34].

Correlations of the physical and energetic properties of the wood with colorimetry parameters were found [20]. Near-infrared (NIR) spectroscopy was also evaluated with the same objective [21]. Both methods were effective in separating waste.

Lima et al. [20] reported that woods with greater red pigmentation (*M. elata* and *D. excelsa* had higher energy density. All groups formed by PCA can be recommended for bioenergy; however, the group formed by the species *M. elata* and *D. excelsa*, with a purplish-brown color, is the most promising.

In general, waste segregation increases carbonization efficiency, mainly due to the effect of wood basic density. High-density waste has less moisture, allowing to add a greater amount of wood mass in the kiln, increasing production and productivity per carbonization cycle. Figure 1 shows the productivity parameters of segregated and non-segregated woods in the different studies carried out during the execution of the project.

Lima et al. [22] reported a species effect on the physical, chemical, and energy properties of charcoal derived from SFMP wastes. The results showed that the content of extractives in the wood positively influenced the gravimetric yields of charcoal, the carbonization mass balance, the heating value, and the energy performance index of charcoal. Apparent relative density, gravimetric yields of charcoal, gravimetric yields of non-condensable gases, ash content, fixed carbon yield, energy density, energy yield, and retained carbon were the properties with a wide variation between species. The PCA separated charcoal samples from SFMP wastes of 48 species into five distinct groups. These groups can be used in carbonization in brick kilns to supply the Carajás Steel Pole and cogeneration systems in remote Amazonian communities. Finally, the *D. excelsa* species wastes showed the best charcoal properties and processes.

Table 1 presents the project outputs to date. Seven articles were published aiming to understand the waste properties and improve charcoal production through its segregation.

Currently, the project "Generation of bioenergy from wastes from sustainable forest management: decentralization of the energy matrix and socio-environmental impacts in Amazonia" (CNPq/MCTI/FNDCT No. 59/2022) is in effect. The project aims to clarify the combustibility processes of burning co-products from SFMP in

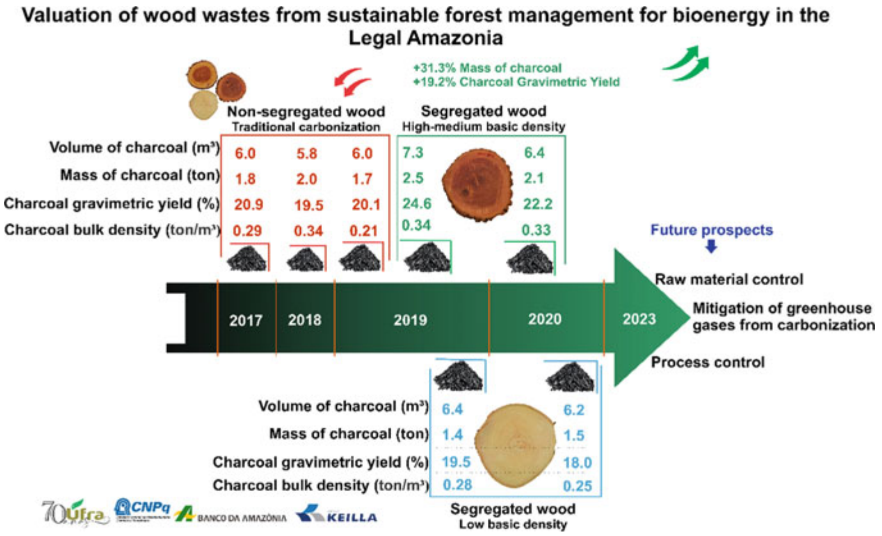

Fig. 1 Summary of results related to kiln productivity during project execution (*Source* The authors 2023)

Amazonia and mitigate the emission of greenhouse gases during the wood carbonization by implementing a furnace-kiln system, which allows the burning of gases formed during the carbonization.

3 Traditional Production of Charcoal from SFMP Wastes in Amazonia

The model of charcoal production in Brazilian Amazonia mainly includes rudimentary brick kilns of the hot tail type, which are semi-spherical kilns built by combining clay and sandy textured soil to avoid cracking. These relatively simple, handmade kilns present low conversion efficiency and are empirically controlled by experienced workers based on the color and amount of smoke expelled, in addition to touch. Consequently, these brick kilns have low productivity and gravimetric yields of charcoal between 15 and 25% on a wet basis [33, 34]. Typically, brick kilns do not include gas cleaning systems and may release unburned by-products into the environment [42]. A typical hot tail kiln is presented in Fig. 2.

The study conducted by Barros et al. [5] describes the carbonization model with wastes in Amazonia. The authors reported kilns with a base diameter of 3.20 m and a height of 2.5 m, with six openings at the base, six at the top, and one chimney, with a height of 70 cm for gas exhaustion. The kilns have a capacity of 10 m^3 of wood. The carbonization cycle normally ranges from 12 to 13 days, including filling, ignition, carbonization, cooling, and kiln discharge steps. The cooling stage refers

Table 1 Products of the project financed directly by the Banco da Amazônia "Valuation of wood wastes from sustainable forest management for bioenergy in Legal Amazonia"

Article	Goal	References
Logging wastes from sustainable forest management as alternative fuels for thermochemical conversion systems in Brazilian Amazon	Energy characterization of the wood wastes from twenty commercial Amazon species harvested in an SFMP and their energy equivalence to fossil fuels	[19]
Charcoal of logging wastes from sustainable forest management for industrial and domestic uses in the Brazilian Amazon	Characterization and production of charcoal from groups of wastes from SFMP in Amazonia according to their physical, chemical, and energy properties	[22]
Grouping of wood wastes from sustainable forest management aiming at bioenergy generation	Grouping of wood wastes from SFMP for firewood and charcoal production for steelmaking	[34]
Colorimetry as a criterion for segregation of logging wastes from sustainable forest management in the Brazilian Amazon for bioenergy	Use of wood color parameters to segregate SFMP wastes	[20]
Efficiency of near-infrared spectroscopy in classifying Amazonian wood wastes for bioenergy generation	Presentation of a method for classifying wood wastes from 12 Amazonian hardwoods based on near-infrared spectroscopy (NIR) and basic density	[24]
Classifying waste wood from Amazonian species by near-infrared spectroscopy (NIRS) to improve charcoal production	Classification of wood waste from 12 Amazonian species by near-infrared spectroscopy (NIRS) to improve charcoal production	[21]
Clarifying the carbonization temperature effects on the production and apparent density of charcoal derived from Amazonia wood wastes	Presentation of the effects of final carbonization temperature and different species of Amazonian wood on carbonization efficiency and apparent relative density of charcoal	[18]
Does the segregation of wood waste from Amazonia improve the quality of charcoal produced in brick kilns?	Comparison of the quality of charcoal derived from wood wastes previously segregated into four distinct and non-segregated groups of 23 Amazonian species carbonized in brick kilns	[5]

to the application of water mixed with clay on the kiln wall (Fig. 3a), with the aid of a tractor (Fig. 3b), intending to seal the kilns and reduce their internal temperatures to about 50 °C, which reduces the chances of charcoal reignition after opening the kiln.

Allied to the low technological apparatus used in the charcoal production model, the raw material used is very heterogeneous (Fig. 4). Typical wood wastes present low energy density, high moisture content, and variable diameters, hindering their use as energy sources, mainly for charcoal production with suitable quality for domestic and industrial applications. The empiricism of the activity is also related to raw material

Fig. 2 Rudimentary brick kiln commonly used in charcoal production with SFMP wastes in Brazilian Amazonia (*Source* The authors 2023)

Fig. 3 Cooling of the kilns through the application of water and clay (**a**) with the aid of a tractor, Massey Ferguson 275 model (**b**) (*Source* The authors 2023)

control, as it is carbonized without diametric standardization and moisture control. It is known that the higher the water content in wood, the lower its heating value, and the combustion will occur in an inadequate regime [12]. In addition, the charcoal yield reduces since the energy expenditure for the process's first stage, drying, is likely to be high. Canal et al. [7] demonstrated that the emissions of condensable gases (pyroligneous liquid) and non-condensable gases (CO_2, CO, CH_4, and H_2) increased, and the gravimetric yield of charcoal decreased with the increase in wood moisture during the carbonization processes.

Currently, there is no control over the moisture content of forest wastes for charcoal production in Legal Amazonia and, consequently, there is the excessive expenditure of energy, the appearance of cracks and internal fissures in the charcoal due to the sudden release of water in the form of steam and, consequent decrease

Fig. 4 SFMP wastes in the storage yard of a charcoal production unit in Brazilian Amazonia (*Source* The authors 2023)

in the mechanical properties of charcoal. Moreover, countless forest species are carbonized concomitantly; therefore, the wood's qualitative and quantitative aspects are not under control. Finally, it is necessary to improve carbonization by, for example, adjusting the process control ranges as a function of time and temperature, considering the thermal degradation of wood to maximize charcoal yield [8, 10, 30].

The effect of raw material heterogeneity and empirically controlled carbonization on charcoal production can be evidenced by data from a Brazilian Amazonia production unit (Table 2). SFMP wastes are carbonized in this production unit, especially branches. Table 2 shows the mass and volume balances obtained in twelve brick kilns in 2017, as well as the descriptive statistics associated with the analyzed variables.

The average values of the wet mass of wastes in the kiln (MW), estimated dry mass of wastes in the kiln (MSM), and estimated volume of wastes in the kiln (VW) obtained by the traditional carbonization model were 8.456 ± 0.371 t, 6.577 ± 0.295 t, and 17.16 ± 0.86 st, respectively. The evaluated kilns produce, on average, 1.762 ± 0.126 t of charcoal per cycle. The average volume of charcoal in the hot tail kilns was 6.01 ± 0.36 m^3.

The gravimetric and volumetric surveys performed were based on the operational conditions of the charcoal production unit and not necessarily on experimental conditions, which, in turn, are controlled. In this way, the factors inherent to the raw material, labor, and the control of carbonization can considerably affect the production and productivity of hot tail kilns. This effect can be verified by analyzing the mass of semi-carbonized pieces (MSP) produced per cycle, in which kiln 4 did not produce these by-products. In contrast, kiln 6 produced a high amount of semi-carbonized pieces (1.240 t) and, consequently, a low gravimetric yield of charcoal. Therefore, they cannot be considered wood or charcoal but a by-product of carbonization.

Table 2 Mass and volume balances per carbonization cycle of SFMP wastes in Brazilian Amazonia

Kiln	MW (t)	VW (st)	MSM (t)	Mch (t)	Vch (m^3)	MSP (t)
1	8.010	16.57	6.312	1.725	6.26	0.140
2	8.250	14.86	6.501	1.455	5.38	0.580
3	9.250	17.10	7.290	1.759	5.69	0.860
4	8.420	15.31	6.635	2.027	6.91	0.000
5	8.400	15.82	6.620	1.793	6.05	0.320
6	9.050	18.99	6.945	1.460	5.21	1.240
7	7.790	17.16	5.978	1.395	4.76	0.460
8	7.470	17.29	5.733	1.640	5.78	0.620
9	8.510	18.64	6.531	1.884	6.33	0.220
10	8.830	18.79	6.777	2.011	7.03	0.100
11	9.900	20.00	7.700	2.156	6.81	0.220
12	7.590	15.33	5.903	1.837	5.88	0.320
Average	8.456	17.16	6.577	1.762	6.01	423.3
CV (%)	8.46	9.70	8.64	13.75	11.68	83.98

MW wet mass of wastes in the kiln (in tons, t); *VW* estimated volume of wastes in the kiln (in stereo, st); *MSM* estimated dry mass of wastes in the kiln (t); *Mch* mass of charcoal (t); *Vch* volume of charcoal (in cubic meters, m^3); *MSP* mass of semi-carbonized pieces (t); *CV* coefficient of variation (%) (*Source* The authors 2017)

The following variations were reported for the gravimetric yield of charcoal—GYC (%, on a wet and dry mass basis) and gravimetric yield of semi-carbonized pieces—GYS (%, on a wet and dry mass basis): 16.13–24.20% (GYC, wet mass basis), 21.02–31.12% (GYC, dry mass basis), 0.00–13.70% (GYS, wet mass basis), and 0.00–17.85% (GYS, dry mass basis) (Table 3).

The production of semi-carbonized pieces is undesirable, as it decreases the kilns' production and productivity (Fig. 5a) and the gravimetric conversion coefficient (Fig. 5b). Kiln 6 presented GYC, wet mass basis, of 16.13%. Kilns 4 and 12, on the other hand, with lower production of semi-carbonized pieces, stood out in converting wood into charcoal. As already mentioned, the generation of semi-carbonized pieces is related to the raw material and the control of carbonization.

The kilns evaluated showed, on average, a GYC of 20.87 ± 1.35% (wet mass basis) and 26.84 ± 1.73% (dry mass basis). The GYS was 5.00 (based on wet mass) and 6.44% (based on dry mass), with high variation between kilns. These results indicate that the carbonization was performed differently in the kilns, probably due to the empirical character associated with charcoal production (lack of control based on specific temperature ranges and time).

Figure 6 shows the gravimetric yields of products and by-products generated in a charcoal production unit concerning the initial total wet mass (110.74 t). 67.51% of forest wastes are transformed into gases during carbonization, 19.09% result in

Table 3 Gravimetric yields of charcoal and semi-carbonized pieces per brick kiln in a charcoal production unit in Brazilian Amazonia

Kiln	GYC (%)		GYS (%)	
	Wet basis	dry basis	Wet basis	Dry basis
1	21.54	27.33	1.75	2.22
2	17.64	22.38	7.03	8.92
3	19.02	24.13	9.30	11.80
4	24.07	30.55	0.00	0.00
5	21.35	27.09	3.81	4.83
6	16.13	21.02	13.70	17.85
7	17.91	23.33	5.91	7.69
8	21.95	28.61	8.30	10.81
9	22.14	28.85	2.59	3.37
10	22.77	29.68	1.13	1.48
11	21.78	28.00	2.22	2.86
12	24.20	31.12	4.22	5.42
Average	20.87	26.84	5.00	6.44
CV (%)	12.46	12.42	80.10	80.53

GYC gravimetric yield of charcoal on a wet and dry basis (%); *GYS* gravimetric yield of semi-carbonized pieces on a wet and dry basis (%); *CV* coefficient of variation (%) (*Source* The authors 2017)

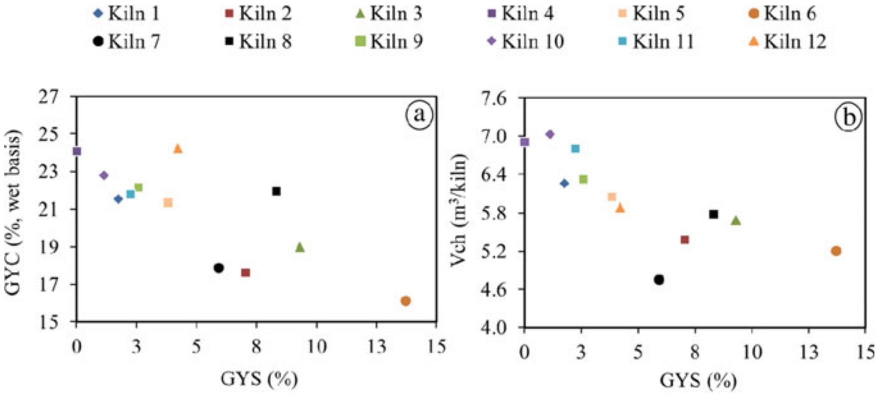

Fig. 5 Relationship between the gravimetric yield (GYC) (**a**) and volume of charcoal (**b**) with the gravimetric yield of semi-carbonized pieces (GYS) in the brick kilns of a charcoal production unit in Brazilian Amazonia (*Source* The authors 2017)

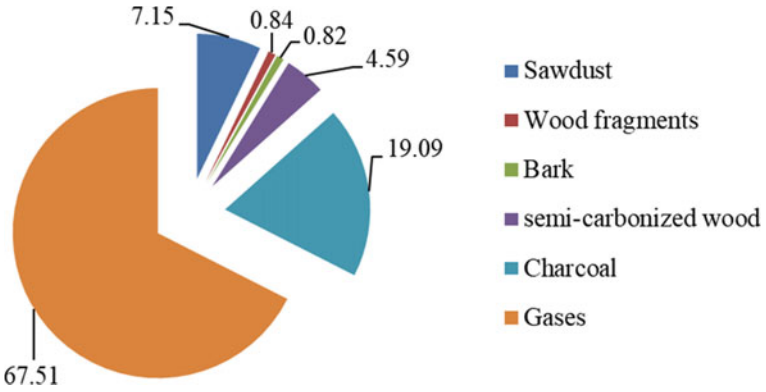

Fig. 6 Gravimetric yields of products and by-products generated in charcoal production, considering the initial total mass with 22.22% of moisture (*Source* The authors 2017)

charcoal, 4.59% in semi-carbonized pieces, and 8.81% are by-products generated in the sectioning wastes (sawdust, wood fragments, and bark).

The charcoal bulk density per kiln (CBD) evaluated in 2017 and the average value obtained for this initial prospecting can be seen in Fig. 7. On average, the CBD of waste was 0.293 t/m^3. The variation between the kilns was low; consequently, the minimum (0.270 t/m^3) and maximum (0.317 t/m^3) values were similar.

In summary, using different species with different physicochemical properties without prior separation for carbonization, combined with the diametric differences of the waste logs and empirical control of carbonization, help explain the previously reported results. Thus, alternatives are needed to maximize kiln productivity based on raw material and process control.

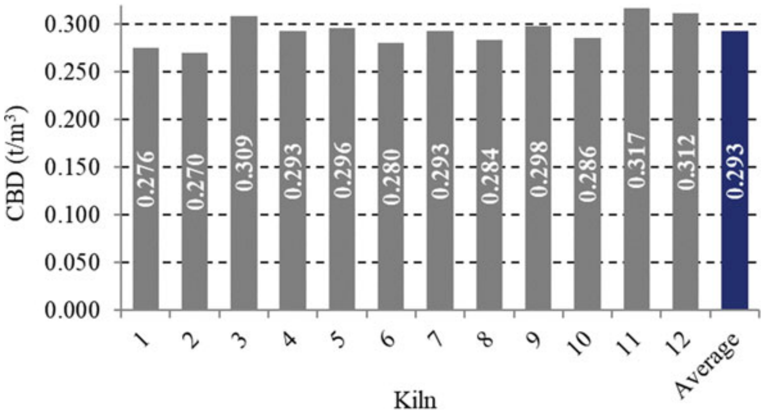

Fig. 7 Charcoal bulk density (CBD) per kiln evaluated in the production unit in Brazilian Amazonia (*Source* The authors 2017)

4 Characteristics of Wood Wastes from SFMP

According to previously published studies, the physical, chemical, and energy properties of SMFP wood wastes corroborate wide heterogeneity [19]. In addition, it is a heterogeneous biomass concerning diameter classes, formats, and origins (root, stem, and branches). A diametric variation of 0.123–0.760 m was reported by Barros et al. [5] for carbonized wastes in brick kilns in Amazonia. The wide variation in wood properties negatively influences charcoal production [23]. In addition, the need to classify woods based on diameter is highlighted since this property strongly influences the thermal profile, heat transfer, and carbonization rate [14, 17].

Regarding the physical properties of wastes, the basic density and moisture have already been studied. Pereira et al. [34] reported a variation of 0.221 (*Sterculia pruriens*) at 0.867 g/cm^3 (*Pseudopiptadenia psilostachya*), evaluating wood wastes of 18 tropical species from Brazilian Amazonia. Values ranging from 0.525 (*Couratari guianensis*) to 0.895 g/cm^3 (*M. elata*) were described by Lima et al. [19], evaluating wood wastes of 20 native species to the Amazonia. More recently, evaluating wood wastes with the near-infrared (NIR) spectroscopy technique, Lima et al. [24] reported basic density values between 0.354 (*Simara guianensis*) and 0.927 g/cm^3(*D. excelsa*).

A compilation of average waste basic density values from the previous studies and the basic density classes proposed by the International Association of Wood Anatomists [16] is shown in Table 4. Three classes were used, namely: low density ($\text{Db} \leq 0.500$ g/cm^3); medium density ($0.500 < \text{Db} \leq 0.720$ g/cm^3); and high density ($\text{Db} > 0.720$ g/cm^3). These are 55 tropical species, ranging from 0.221 to 0.935 g/cm^3.

The amplitudes reported for Amazonian wood wastes are within the variation range (0.140–1.210 g/cm^3) published by Fearnside [13], evaluating the wood properties of 268 tropical species from the same biome. The literature demonstrates that low-density woods (< 0.500 g/cm^3) are not suitable for energy purposes. Thus, they should not be carbonized with the high basic density woods to produce bioreducers.

In the reality of Amazonia, wood in all density ranges is carbonized, negatively influencing the gravimetric yield and charcoal productivity of brick kilns. Protásio et al. [37] reported a positive relationship between wood basic density and charcoal apparent relative density of *Eucalyptus* sp., indicating that denser woods result in dense charcoals.

Pereira et al. [34] also reported moisture values under operational conditions ranging from 24.99 (*Cordia goeldiana*) to 159.26% (*Sterculia* sp.) on a dry basis. Moisture is negatively correlated with the wood basic density [24], indicating that high-density woods present lower moisture due to the smaller volume of empty spaces in the wood [31]. For energy purposes, woods with moisture below the fiber saturation point (< 30%, dry basis) are recommended. Above that, the negative effects are significant in the gravimetric yield of charcoal, as a considerable part of the firewood is burned to release energy to meet the drying stage, as well as in the carbonization cycle, making it longer. In this sense, greater control of the moisture of wood wastes under operational conditions is necessary.

Table 4 Basic density of wood wastes of tropical species from Brazilian Amazonia

N	Species	Commercial name	BD (g/cm^3)	Class
1	*Sterculia pruriens*	Envira-quiabo	0.221 ± 0.016	Low
2	*Simaba guianensis*	Marupá-amarelo	0.354 ± 0.015	Low
3	*Simarouba amara*	Marupá	0.367 ± 0.015	Low
4	*Sterculia* sp.	Sucupira-babona	0.377 ± 0.052	Low
5	*Protium* sp.2	Breu-amesclim	0.392 ± 0.007	Low
6	*Tapirira guianensis*	Tapiririca	0.397 ± 0.017	Low
7	*Parkia gigantocarpa*	Fava-atanã	0.436 ± 0.033	Low
8	*Ocotea* sp.2	Louro-amarelo	0.452 ± 0.022	Low
9	*Cordia goeldiana*	Freijó	0.457 ± 0.023	Low
10	*Ocotea* sp.3	Louro-preto	0.470 ± 0.042	Low
11	*Anacardium giganteum*	Cajuaçu	0.486 ± 0.020	Low
12	*Parkia* sp.	Fava-branca	0.501 ± 0.010	Medium
13	*Couratari guianensis*	Tauarí-liso	0.525 ± 0.050	Medium
14	*Tetragastris altissima*	Amesclim	0.545 ± 0.042	Medium
15	*Couratari oblongifolia*	Tauarí-branco	0.545 ± 0.033	Medium
16	*Pouteria* sp.1	Guajará-bolacha	0.574 ± 0.028	Medium
17	*Ocotea* sp.1	Canela	0.586 ± 0.038	Medium
18	*Brosimum gaudichaudii*	Inharé	0.599 ± 0.006	Medium
19	*Peltogyne* sp.	Roxinho	0.641 ± 0.038	Medium
20	*Sclerolobium* sp.	Tachi	0.642 ± 0.042	Medium
21	*Pouteria* sp.5	Guajará-bolacha	0.667 ± 0.044	Medium
22	*Protium* sp.1	Breu-barrote	0.683 ± 0.057	Medium
23	*Pouteria oblanceolata*	Abiu	0.683 ± 0.038	Medium
24	*Vatairea sericea*	Angelim-amargoso	0.686 ± 0.051	Medium
25	*Lecythis* sp.	Sapucaia	0.690 ± 0.117	Medium
26	*Vantanea parviflora*	Uxirana	0.699 ± 0.070	Medium
27	*Pouteria* sp.4	Abiorana	0.701 ± 0.075	Medium
28	*Pouteria* sp.3	Abiorana	0.701 ± 0.061	Medium
29	*Caryocar* sp.2	Pequiarana	0.701 ± 0.029	Medium
30	*Caryocar glabrum*	Pequiarana	0.702 ± 0.074	Medium
31	*Caryocar villosum*	Pequiá	0.711 ± 0.048	Medium
32	*Protium altissimum*	Breu-barrote	0.721 ± 0.030	High
33	*Eschweilera pedicellata*	Matamatá	0.724 ± 0.045	High
34	*Eschweilera amazonica*	Jiboião	0.728 ± 0.050	High
35	*Pseudopiptadenia suaveolens*	Timborana	0.744 ± 0.086	High
36	*Eschweilera grandiflora*	Matamatá-preto	0.749 ± 0.057	High

(continued)

Table 4 (continued)

N	Species	Commercial name	BD (g/cm^3)	Class
37	*Goupia glabra*	Cupiúba	0.752 ± 0.035	High
38	*Pouteria* sp.2	Guajará-cinza	0.754 ± 0.011	High
39	*Lecythis lurida*	Jarana	0.755 ± 0.031	High
40	*Eschweilera* sp.1	Matamatá	0.779 ± 0.078	High
41	*Eschweilera coriacea*	Matamatá-branco	0.785 ± 0.012	High
42	*Eschweilera* sp.2	Matamatá	0.792 ± 0.029	High
43	*Parinari rodolphii*	Coco-pau	0.801 ± 0.046	High
44	*Caryocar* sp.1	Pequiá	0.802 ± 0.016	High
45	*Manilkara* sp.1	Maçaranduba	0.806 ± 0.079	High
46	*Hymenaea* sp.	Jatobá	0.811 ± 0.130	High
47	*Lecythis pisonis*	Sapucaia	0.812 ± 0.064	High
48	*Terminalia* sp.	Tanibuca	0.814 ± 0.021	High
49	*Enterolobium schomburgkii*	Orelha-de-macaco	0.836 ± 0.036	High
50	*Vantanea guianensis*	Uxirana	0.843 ± 0.114	High
51	*Licania canescens*	Casca-seca	0.858 ± 0.047	High
52	*Pseudopiptadenia psilostachya*	Timborana	0.867 ± 0.074	High
53	*Manilkara* sp.2	Maçaranduba	0.872 ± 0.010	High
54	*Manilkara elata*	Maçaranduba	0.903 ± 0.023	High
55	*Dinizia excelsa*	Angelim-vermelho	0.935 ± 0.044	High

N species number; *BD* wood basic density (g/cm^3). Commercial name in Brazil. Average ± standard deviation (*Source* The authors 2023)

Average values of the chemical properties of wood wastes, such as total lignin (LigT), total extractives (EXT), and elemental carbon (C), can be seen in Table 5. These are data on wood from branches of 20 logged tropical species by the reduced impact logging method in an SFMP certified by the Forest Stewardship Council (FSC) in Brazilian Amazonia, previously published by Lima et al. [19].

EXT (1.8–17.9%, dry mass basis), LigT (30.2–38.1, dry mass basis free of extractives), and C (49.2–52.4%, basis mass dry) demonstrated high variability in native tropical woods of Amazonia. Wood species with high levels of EXT, LigT, and C are promising for energy purposes, especially to supply the charcoal-producing complex in the Carajás region, located between Maranhão and Pará states, in Brazil. Lima et al. [23] demonstrated that the EXT had a positive relationship with the GYC, indicating that the species *D. excelsa*, *P. altissimum, M. elata,* and *G. glabra* showed the best carbonization mass balances.

The C value (42.82%) described by Haqiqi et al. [15] for *Eucalyptus pellita* and the variation range (47.23–48.80%) reported by Santos et al. [40] of four *Eucalyptus* hybrid clones (three *Eucalyptus urophylla* × *E. grandis* and one *Eucalyptus camaldulensis* × *E. grandis*) at seven years of age, were lower than the values found

Table 5 Total extractives, total lignin, and elemental carbon from SFMP wastes in Brazilian Amazonia

Species	Commercial name	EXT (%)*	LigT (%)**	C (%)*
Dinizia excelsa	Angelim-vermelho	17.9	37.6	51.7
Protium altissimum	Breu-barrote	12.6	31.0	50.9
Manilkara elata	Maçaranduba	11.9	30.2	51.0
Goupia glabra	Cupiúba	11.4	34.0	51.0
Pouteria sp. 2	Guajará-bolacha	9.0	33.3	50.3
Pouteria oblanceolata	Abiu	9.0	32.3	50.6
Lecythis lurida	Jarana	8.4	34.3	49.7
Pseudopiptadenia suaveolens	Timborana	8.0	32.9	52.0
Eschweilera grandiflora	Matamatá-preto	7.7	30.9	49.2
Caryocar glabrum	Pequiarana	7.7	32.6	50.7
Enterolobium schomburgkii	Orelha-de-macaco	6.0	33.0	51.8
Eschweilera pedicellata	Matamatá	6.0	32.4	52.4
Lecythis pisonis	Sapucaia	5.9	33.5	52.2
Couratari guianensis	Tauarí-liso	5.3	33.6	49.9
Caryocar villosum	Piquiá	4.9	34.5	51.0
Pouteria sp. 1	Abiorana	4.0	33.6	50.1
Couratari oblongifolia	Tauarí-branco	3.8	32.6	49.7
Licania canescens	Casca-Seca	3.6	36.6	49.7
Vantanea parviflora	Uxirana	2.4	33.3	50.0
Parinari rodolphii	Coco-pau	1.8	38.1	50.9

EXT total extractives (%); *LigT* total lignin (%); and *C* elemental carbon (%). *Based on dry wood mass. ** Based on dry wood mass free of extractives (*Source* Lima et al. [19])

for wood wastes, which ranged from 49.2 to 52.4%. This range of C indicates that the wastes are very promising since C is the main energetic element of biomass [2]. Woods of the *Eucalyptus genus* are the most used to compose energy forests, Brazil's main source of forest biomass. Thus, alternative renewable sources are important for diversifying the energy sector's raw materials.

Pereira et al. [35] discussed that woods with LigT above 28% are desired for charcoal production. All species shown in Table 5 showed values above the reference published by the authors, indicating that the species are suitable for this purpose. Wood species with high LigT values are more thermally stable and contribute positively to the gravimetric yield of charcoal of the production unit [27]. In addition, they have a high heating value, which indicates more energy is generated during combustion [43].

Although wastes from SFMP have suitable quality for charcoal production, the carbonization of wood with different physical and chemical characteristics negatively affects charcoal production unity, productivity in brick kilns, and the quality of the charcoal produced. Barros et al. [5] demonstrated that the carbonization of different woods together, which is the traditional model of carbonization in Amazonia, results in a reduction in the charcoal quality, negatively affecting friability, apparent relative density, ash content, volatile matter, fixed carbon, higher heating value, and energy density. The authors highlighted the need for better control of the raw material factor under operational conditions, especially with the wood segregation before carbonization, aiming to reduce the effect of heterogeneity on the production, productivity, and quality of the charcoal produced in traditional kilns.

5 Carbonization of Similar Wood Wastes

Several proposals were presented in the literature to reduce the heterogeneity of the residual raw material to produce charcoal based on the properties of the wood [19, 20, 34] and charcoal [23]. Carbonization should prioritize woods with similar properties to homogenize the process phases and the bioreducer quality. The wood basic density can be a criterion to separate wastes, as well as several combined properties, through multivariate statistical analyses of grouping.

Pereira et al. [34] proposed carbonization considering basic density classes. In this study, the authors separate wood wastes into classes of low (*Sterculia pruriens, Sterculia* sp., and *Cordia goeldiana*), medium (*Tetragastris altissima, Pouteria* sp., *Ocotea* sp., *Peltogyne* sp., *Sclerolobium* sp., *Protium* sp., *Lecythis* sp., and *Caryocar villosum*), and high (*Eschweilera amazonia, Lecythis lurida, Eschweilera* sp., *Manilkara* sp., *Hymenaea* sp., *Terminalea* sp., and *Pseudopiptadenia psilostachya*) density. They recommended wood of medium and high basic density for steel charcoal production, as it will result in a bioreducer with adequate apparent relative density.

Lima et al. [19] verified four groups of similar residual woods through the PCA technique, using physical (basic density, moisture, and maximum moisture content); chemical (proximate analysis: fixed carbon, volatile matter, and ash; and molecular analysis: total extractives, soluble, insoluble, and total lignin); and energy (higher heating value and energy density) properties; in addition to the specific consumption of firewood in charcoal production. This proposal promoted improvements of (+) 22, (−) 9.4, (+) 2.0, (−) 2.3, (+) 1.0, and (+) 23.6% in apparent relative density, ash content, fixed carbon, friability, higher heating value, and energy density of charcoal produced in brick kilns in Amazonia [5]. Table 6 presents the wood groups evaluated by the authors and the basic density variation ranges.

Lima et al. [23] used the same grouping analysis to separate species in charcoal production units in Amazonia based on physical, chemical, and energy properties. Furthermore, the authors considered the yields of the carbonization process under laboratory conditions. Colorimetric characteristics (lightness, green/red axis, blue/yellow axis, color saturation, and hue angle), physical (moisture and basic density), chemical (total extractives and total lignin), and energy density of these residual woods contributed to the formation of six species groups using the PCA technique

Table 6 Species groups segregated by PCA technique for carbonization in a charcoal production unit in Brazilian Amazonia

Group 1 (BD: 0.948–1.015 g/cm^3)	Group 2 (BD: 0.787–0.914 g/cm^3)	Group 3 (BD: 0.429–0.711 g/cm^3)	Group 4 (BD: 0.568–0.936 g/cm^3)	Group 5 (traditional) (BD: 0.352–1.015 g/cm^3)
D. excelsa	*P. rodolphii*	*A. giganteum*	*Pouteria* sp.1	*A. giganteum*
	L. canescens	*C. oblongifolia*	*V. sericea*	*C. glabrum*
		Ocotea sp.1	*P. altissimum*	*C. villosum*
		Ocotea sp.2	*G. glabra*	*C. oblongifolia*
		Pouteria sp.2	*L. lurida*	*D. excelsa*
			M. elata	*E. coriacea*
			E. coriacea	*G. glabra*
			C. glabrum	*L. lurida*
			C. villosum	*L. pisonis*
			L. pisonis	*L. canescens*
			P. suaveolens	*M. elata*
			V. guianensis	*Ocotea* sp.1
				Ocotea sp.2
				P. rodolphii
				P. gigantocarpa
				Pouteria sp.1
				Pouteria sp.2
				P. altissimum
				Protium sp.
				P. suaveolens
				S. amara
				V. guianensis
				V. sericea

BD basic density (g/cm^3) (*Source* [5])

[20]. In the study, the basic and energy densities were negatively correlated with lightness, blue/yellow axis, color saturation, and hue angle, demonstrating that darker woods, such as *D. excelsa* and *M. elata,* present greater energy potential.

Two methods were tested to segregate residual wood on an operational scale. The first was based on the basic density [34], and the second was based on several characteristics of the wood [19]. In this sense, positive effects are evident in the productivity of brick kilns with raw material control. Figure 8 shows the effects of separating wood into density classes (medium–high and medium–low) on charcoal production at an operational scale.

Medium–high basic density woods (0.739–0.993 g/cm^3) had lower average MC (41.1%, dry mass basis), while medium–low basic density woods (0.517–0.630 g/cm^3) had higher MC (67.5%, based on dry mass). The trend of water reduction in woods with high BD can be seen in Fig. 9a. Traditional carbonization brings

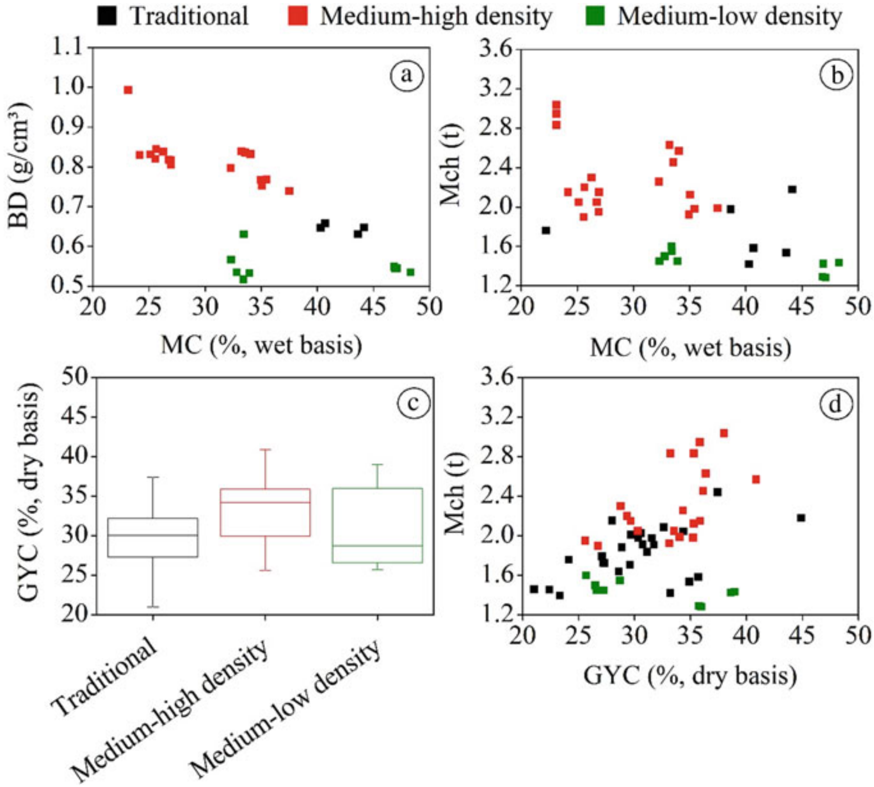

Fig. 8 Effects of waste segregation into density classes (medium–high and medium–low) on charcoal productivity at operational scale in Brazilian Amazonia. Relationship between basic density—BD (g/cm^3) and moisture content—MC (%) (**a**), mass of charcoal—Mch (t) and MC (%) (**b**), basic density—BD (g/cm^3) and gravimetric yield of charcoal—GYC (%) (**c**), and GYC (%) and Mch (t) (**d**) (*Source* The authors 2023)

together woods with a wide variation in BD, which is not interesting due to the different MCs of the woods, which makes it difficult to control the carbonization process, reducing Mch (Figs. 9b and d) and GYC (Fig. 9c). Traditional carbonization showed a GYC of 30.3% (based on dry mass), lower than the average values reported for the medium–high (33.4%, based on dry mass) and medium–low wood groups (31.6%, based on dry mass) density. It is important to note that traditional carbonization negatively affects bioreducer production, the unit's operational efficiency, and revenues. Segregation promotes greater production of charcoal with the same quantity of wood mass inserted in the kiln. From an operational and charcoal productivity point of view, BD as a criterion to separate residual wood is the most appropriate and simple method to be carried out by the employees.

Additional wood characteristics can be used as a separation criterion to improve the production and quality of the steel bioreducer. In this sense, the carbonization of the groups proposed by Lima et al. [19] was tested under operational conditions in brick kilns. Figure 9 presents weighted average data for moisture—MCw (Fig. 9a) and basic density—BDWw (Fig. 9b), wet mass—MW (Fig. 9c), and volume—VW (Fig. 9d) of wood per hot-tail kiln. Groups 2 (9.117 m^3) and 3 (9.500 m^3) filled the kilns with the highest average volumes of waste. Groups 1, 2, and 4 showed average MW, MCw, and BDWw above group 5 (conventional model).

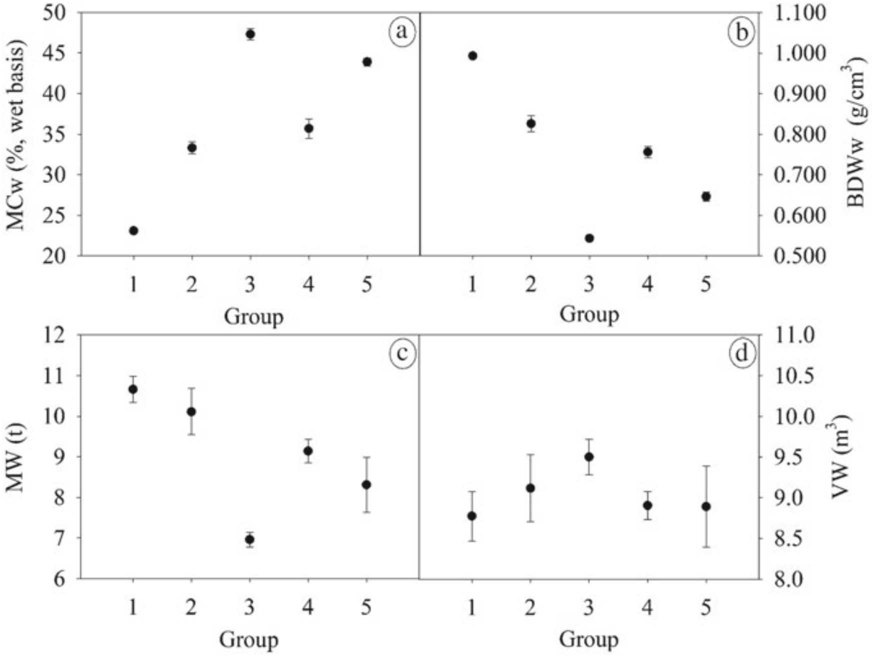

Fig. 9 Weighted moisture content of the wastes (**a**), weighted basic density of wastes (**b**), wet mass of wood (**c**), and volume of wood (**d**) by waste groups in brick kilns in Brazilian Amazonia. Error bars refer to standard deviations (*Source* The authors 2023)

Waste groups 1, 2, and 4, which combine medium and high-density species, had the highest MW. Consequently, they allowed better use of the kiln's internal space. In addition, such combined wood species had lower MCw and higher BDWw. The woods in group 3 presented a lower MW inside the kiln due to the lower BDWw. In summary, grouping similar tropical woods provided encouraging results related to the wood amount inserted in the kilns. It is known that the greater the dry wood mass in the kiln, the greater the mass of charcoal produced. The traditional model of carbonization promotes greater variation in the MW, and VW used in the process, which is not interesting, as it makes the monthly and annual planning of wood in the charcoal plant difficult.

Compared to the traditional model without wood separation, the charcoal productivity dataset from brick kilns demonstrates the positive effects of waste wood segregation in Amazonia (Fig. 10). In order, groups 1 (7.84 m^3), 2 (7.33 m^3), 4 (6.61 m^3), and 3 (6.43 m^3) showed better average values of charcoal volume (Vch), compared to the group without segregation, which produced 6.02 m^3. Regarding mass (Mch), gravimetric yield (GYC), and bulk density (CBD) of charcoal, the highest average values were reported for groups 1, 2, and 4.

The highest Mch and GYC results reported for group 1 (*D. excelsa*) are associated with the high content of extractives and lignin in the wood (see Table 5). The H/C

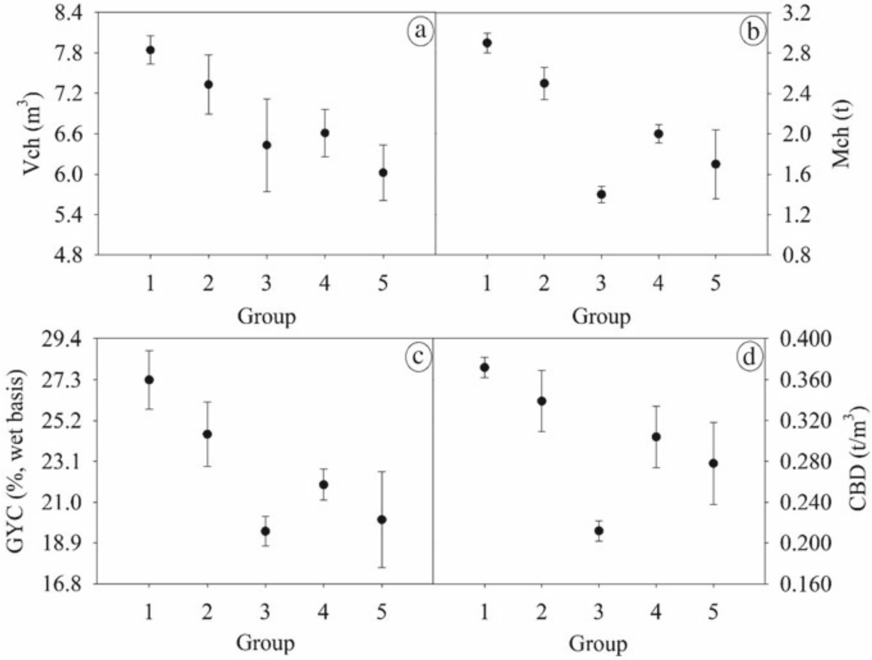

Fig. 10 Volume (**a**), mass (**b**), gravimetric yield (**c**), and bulk density (**d**) of charcoal produced in brick kilns at a production plant in Brazilian Amazonia using segregated waste groups (*Source* The authors 2023)

ratio and the high thermal stability of the extractives, mainly the phenolics, contribute to the increase in Mch and GYC [36]. In addition, this group will present reduced emissions of condensable and non-condensable gases into the atmosphere. Woods with higher densities explain the high CBD mean values of groups 1 (0.372 t/m^3), 2 (0.339 t/m^3), and 4 (0.304 t/m^3). In this sense, segregation will promote a greater mass of charcoal transported to the steel industries compared to group 5. On the other hand, the charcoal of group 3 is less dense and voluminous and can be considered as a basis for commercialization.

The production of charcoal must be better controlled, especially concerning raw materials and factors associated with the process. Clearly, the separation of wood promotes encouraging results related to the production and quality of charcoal, which can influence the operational and financial planning of the plant. Thus, the methodology to adequately control the quality of the consumed raw material must be adjusted. As charcoal is commercialized based on its mass, the basic density can be used as a qualitative index to discriminate the material by its quality. Furthermore, it is an easily determined property. The literature corroborates that dense woods generate charcoals with high apparent relative density [23]. On the other hand, groups with similar physical, chemical, and energy properties can clearly improve charcoal quality.

6 Future Prospects for Charcoal Production from Wood Wastes

The energy use of forest wastes contributes to reducing the environmental impact caused by improper disposal and the exacerbated use of “dirty” energy sources and, consequently, to the mitigation of greenhouse gas emissions. Forest biomass stands out among the various renewable materials used for energy purposes due to the numerous solid, liquid, and gaseous fuels obtained through thermochemical, biochemical, and mechanical routes and their conciliation. It is worth noting that Normative Instruction No. 5, of December 11, 2006, published by the Ministry of the Environment, mentions in Article 2, item XIV, that forest logging wastes (branches, buttresses, and remains of trunks, for example) can be used as secondary products of SFMP for wood and energy production [6]. However, there is still a lack of scientific research and technology transfer for the sustainable valorization of these resources for bioenergy generation on industrial and domestic scales.

Many advances have been obtained with the understanding of the quality of SFMP wastes destined for energy generation and steel charcoal production. However, there is a need to continue research to reach technological maturity for a real understanding of the energy potential of this biomass. Furthermore, converting this raw material into energy products is not sufficiently mastered. In this sense, thermochemical conversion routes must be sufficiently analyzed with integrated methodologies (energetic-environmental-economic). For example, the life cycle inventory will provide a technical–economic-environmental assessment of strategies for the sustainable use of residual biomass in SFMP associated with the carbon balance of conversion processes.

The studies carried out so far have promoted important advances in clarifying the quality parameters of forest wastes destined for energy production. Despite this, some aspects of its energy use need to be elucidated. As pointed out by Lima et al. [19], the thermal behavior and combustion kinetics of this fuel remains unclear. It is also necessary to know the energy performance of the wastes at different final carbonization temperatures. These studies will allow more efficient use of wood and subsidize new conversion routes, such as densification, torrefaction, gasification, and liquefaction. Biomass has been widely studied for producing electricity, bio-oil, and chemical compounds [26]. Although there is research on wood from Amazonian species [38] and other biomass types common in the region [3], there is no large-scale research on woody Amazonian wastes for this purpose.

From a strategic point of view, biomass energy conversion processes are economically viable techniques to generate energy for local communities and industrial production systems, even in remote locals, as in several regions of the Amazonia. In Brazil, direct combustion and carbonization are the two most widespread ways of using wood wastes from SFMP, the main legal tool for the rational use of timber and non-timber forest products in Brazilian Amazonia.

Previously reported studies were limited to a single charcoal production unit from waste wood. Future research needs to include more wooden species and Amazonian forest management regions in their studies. It is also necessary to know the amount of waste stored in the forests. Thus, efficient harvesting and storage strategies for these biomasses must be developed.

The sustainability of the entire production chain for the use of waste must become one of the main objects of future research, generating technological impacts for the full use of waste and improving sustainable technologies for bioenergy use of tropical forest resources; with new, creative, and viable solutions that contribute to technological, economic, and social developments, through research. Thus, the following questions must be answered: (i) How much carbon is emitted from the collection, transport, carbonization, and combustion of waste?; (ii) Does the carbon stored in the forest soil and the regeneration of trees after harvesting neutralize the carbon emitted by the production chain?; (iii) Are the strategies effective in minimizing environmental impacts?

The answers to these questions will support the development of new solutions in Amazonia for increasing the efficiency of waste use and minimizing polluting gas emissions during wood carbonization. The technologies used for planted forests burn polluting gases formed during carbonization [8] and can be improved, adapted, and applied to the carbonization of SFMP wood wastes.

7 Conclusions

SFMP wastes have suitable properties for charcoal production for domestic and industrial use. However, there are great challenges to producing sustainable energy with this Amazonian biomass, mainly due to the low technological level of the carbonization kilns and the high variation in the waste properties concerning their dimensions and physical, chemical, and energy properties.

For example, waste diameter and basic density show high variability among species, studies were carried out to characterize and classify these wood wastes into different groups to solve these problems. The results demonstrate an increase in the gravimetric yield of charcoal, the productivity of the kilns, and an improvement in the bioreducer quality.

Therefore, the importance of technological research is emphasized to enable the development of carbonization, direct heat generation, and other energy routes to adapt the industry in Brazil to the current requirements of the national and international markets. Future research should highlight technological improvements in energy production using SFMP wastes to increase efficiency, quality, and sustainability.

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References

1. Achat DL, Deleuze C, Landmann G, Pousse N, Ranger J, Augusto L (2015) Quantifying consequences of removing harvesting residues on forest soils and tree growth—a meta-analysis. For Ecol Manage 348:124–141. https://doi.org/10.1016/j.foreco.2015.03.042
2. Adamovics A, Platace R, Gulbe I, Ivanovs S (2018) The content of carbon and hydrogen in grass biomass and its influence on heating value. Eng Rural Dev 1(1):1277–1281. https://doi.org/10.22616/ERDev2018.17.N014

3. Araujo RO, Ribeiro FCP, Santos VO, Lima VMR, Santos JL, Vilaça JES, Chaar JS, Falcão NPS, Pohlit AM, de Souza LKC (2022) Renewable energy from biomass: an overview of the Amazon Region. Bioenergy Res 15(2):834–849. https://doi.org/10.1007/s12155-021-10308-x
4. Assis MR, Brancheriau L, Napoli A, Trugilho PF (2016) Factors affecting the mechanics of carbonized wood: literature review. Wood Sci Technol 50(3):519–536. https://doi.org/10.1007/s00226-016-0812-6
5. Barros DS, Lima MDR, Dias Junior AF, Bufalino L, Massuque J, Santos EV, Trugilho PF, Oliveira FA, Protásio TP (2023) Does the segregation of wood waste from Amazonia improve the quality of charcoal produced in brick kilns? Bioenergy Res. https://doi.org/10.1007/s12155-022-10551-w
6. Brazil (2006) Ministry of the Environment. Normative Instruction MMA No. 5 of December 11, 2006. Technical procedures for the preparation, presentation, execution, and technical evaluation of Sustainable Forest Management Plans—SFMP in primitive forests and their forms of succession in the Legal Amazon, and makes other arrangements. Brazil
7. Canal WD, Carvalho AMML, Carneiro ACO, Vital BR, Pereira BLC, Donato DB (2016) Effect of wood moisture on greenhouse gases emission from carbonization process. Sci For 44(112):831–840. https://doi.org/10.18671/scifor.v44n112.05
8. Cardoso MT, Damásio RAP, Carneiro ACO, Jacovine LAG, Vital BR, Barcelos DC (2010) Construction of a gas burning system resulting from carbonization to reduce pollutants emissions. Cerne 16:115–124
9. Crow SE, Reeves M, Turn S, Taniguchi S, Schubert OS, Koch N (2016) Carbon balance implications of land use change from pasture to managed eucalyptus forest in Hawaii. Carbon Manag 7(3–4):171–181. https://doi.org/10.1080/17583004.2016.1213140
10. Damásio RAP, Oliveira AC, Carneiro ACO, Barcelos DC, Pereira BLC, Magalhães MA, Silva MS (2015) Thermal profile and control of carbonization on circular kiln through the internal temperature. Ciência da Madeira 6(1):11–22. https://doi.org/10.12953/2177-6830/rcm.v61p11-22
11. Demirbas A (2005) Potential applications of renewable energy sources, biomass combustion problems in boiler power systems and combustion related environmental issues. Prog Energy Combust Sci 31(2):171–192. https://doi.org/10.1016/j.pecs.2005.02.002
12. Diniz VY (1981) Caldeiras a lenha. In: Gaseificação de madeira e carvão vegetal. pp 114–131
13. Fearnside PM (1997) Wood density for estimating forest biomass in Brazilian Amazonia. For Ecol Manage 90(1):59–87. https://doi.org/10.1016/S0378-1127(96)03840-6
14. Figueroa MJM, Moraes PD (2009) Wood behavior at high temperatures Manuel. Ambiente Construído 9(4):157–174
15. Haqiqi MT, Hudaya D, Septiana HA, Ramadhan R, Yuliansyah Y, Suwinarti W, Amirta R (2022) Short communication: analysis of the ultimate wood composition of a forest plantation species, *Eucalyptus pellita*, to estimate its bioelectricity potency. Biodiversitas 23(5):2389–2394. https://doi.org/10.13057/biodiv/d230516
16. International Association of Wood Anatomists - IAWA (1989) International association of wood anatomists: list of microscopc features for hardwood identification. IAWA J 10(3):219–232
17. Jesus MS, Carneiro ACO, Martinez CLM, Vital BR, Carneiro APS, Assis MR (2019) Thermal decomposition fundamentals in large-diameter wooden logs during slow pyrolysis. Wood Sci Technol 53:1353–1372. https://doi.org/10.1007/s00226-019-01133-9
18. Lima MDR, Massuque J, Bufalino L, Trugilho PF, Ramalho FMG, Protásio TP, Hein PRG (2022) Clarifying the carbonization temperature effects on the production and apparent density of charcoal derived from Amazonia wood wastes. J Anal Appl Pyrolysis 166:105636. https://doi.org/10.1016/j.jaap.2022.105636
19. Lima MDR, Patrício EPS, Barros Junior UO, Assis MR, Xavier CN, Bufalino L, Trugilho PF, Hein PRG, Protásio TP (2020) Logging wastes from sustainable forest management as alternative fuels for thermochemical conversion systems in Brazilian Amazon. Biomass Bioenergy 140:105660. https://doi.org/10.1016/j.biombioe.2020.105660
20. Lima MDR, Patrício EPS, Barros Junior UO, Silva RCC, Bufalino L, Numazawa S, Hein PRG, Protásio TP (2021) Colorimetry as a criterion for segregation of logging wastes from sustainable

forest management in the Brazilian Amazon for bioenergy. Renew Energy 163:792–806. https://doi.org/10.1016/j.renene.2020.08.078

21. Lima MDR, Ramalho FMG, Trugilho PF, Bufalino L, Dias Júnior AF, Protásio TP, Hein PRG (2022) Classifying waste wood from Amazonian species by near-infrared spectroscopy (NIRS) to improve charcoal production. Renew Energy 12(1):3224. https://doi.org/10.1016/j.renene.2022.05.048
22. Lima MDR, Simetti R, de Assis MR, Trugilho PF, de Carneiro ACO, Bufalino L, Hein PRG, de Protásio TP (2020) Charcoal of logging wastes from sustainable forest management for industrial and domestic uses in the Brazilian Amazonia. Biomass Bioenergy 142. https://doi.org/10.1016/j.biombioe.2020.105804
23. Lima MDR, Simetti R, Assis MRD, Trugilho PF, Carneiro ADCO, Bufalino L, Hein PRG, Protásio TDP (2020) Charcoal of logging wastes from sustainable forest management for industrial and domestic uses in the Brazilian Amazonia. Biomass Bioenergy 142:105804. https://doi.org/10.1016/j.biombioe.2020.105804
24. Lima MDR, Trugilho PF, Bufalino L, Dias Júnior AF, Ramalho FMG, Protásio TP, Hein PRG (2022) Efficiency of near-infrared spectroscopy in classifying Amazonian wood wastes for bioenergy generation. Biomass Bioenergy 166:106617. https://doi.org/10.1016/j.biombioe.2022.106617
25. Manolis EN, Zagas TD, Karetsos GK, Poravou CA (2019) Ecological restrictions in forest biomass extraction for a sustainable renewable energy production. Renew Sustain Energy Rev 110:290–297. https://doi.org/10.1016/j.rser.2019.04.078
26. Mednikov AS (2018) A review of technologies for multistage wood biomass gasification. Therm Eng 65(8):531–546. https://doi.org/10.1134/S0040601518080037
27. Moriana R, Vilaplana F, Ek M (2015) Forest residues as renewable resources for bio-based polymeric materials and bioenergy: chemical composition, structure and thermal properties. Cellulose 22(5):3409–3423. https://doi.org/10.1007/s10570-015-0738-4
28. Numazawa CTD, Krasovskiy A, Kraxner F, Pietsch SA (2020) Logging residues for charcoal production through forest management in the Brazilian Amazon: economic gains and forest regrowth effects. Environ Res Lett 15(11):114029. https://doi.org/10.1088/1748-9326/abb495
29. Numazawa CTD, Numazawa S, Pacca S, John VM (2017) Logging residues and CO_2 of Brazilian Amazon timber: two case studies of forest harvesting. Resour Conserv Recycl 122:280–285. https://doi.org/10.1016/j.resconrec.2017.02.016
30. Oliveira AC, Carneiro ACO, Pereira BLC, Vital BR, Carvalho AMML, Trugilho PF, Damásio RAP (2013) Optimization of charcoal production through control of carbonization temperatures. Revista Árvore 37(3):557–566. https://doi.org/10.1590/S0100-67622013000300019
31. Oliveira JTS, Hellmeister JC, Tomazello Filho M (2005) Variation of the moisture content and specific gravity in the wood of seven eucalypt species. Revista Árvore 29(1):115–127. https://doi.org/10.1590/S0100-67622005000100013
32. Paré D, Thiffault E (2016) Nutrient budgets in forests under increased biomass harvesting scenarios. Current Forestry Reports 2(1):81–91. https://doi.org/10.1007/s40725-016-0030-3
33. Peláez-Samaniego MR, Garcia-Perez M, Cortez LB, Rosillo-Calle F, Mesa J (2008) Improvements of Brazilian carbonization industry as part of the creation of a global biomass economy. Renew Sustain Energy Rev 12(4):1063–1086. https://doi.org/10.1016/j.rser.2006.10.018
34. Pereira AA, Lima MDR, Patrício EPS, Numazawa S, Goulart SL, Protásio TP (2020) Grouping of wood residues from sustainable forest management aiming at bioenergy generation. Sci For 48(127):1–14. https://doi.org/10.18671/scifor.v48n127.01
35. Pereira BLC, Carneiro ACO, Carvalho AMML, Colodette JL, Oliveira AC, Fontes MPF (2013) Influence of chemical composition of Eucalyptus wood on gravimetric yield and charcoal properties. Bioresources 8(3):4574–4592. https://doi.org/10.15376/biores.8.3.4574-4592
36. Pereira BLC, Oliveira AC, Carvalho AMML, Carneiro ACO, Santos LC, Vital BR (2012) Quality of wood and charcoal from Eucalyptus clones for ironmaster use. Int J For Res 2012:1–8. https://doi.org/10.1155/2012/523025

37. Protásio TP, Lima MDR, Scatolino MV, Silva AB, Figueiredo ICR, Hein PRG, Trugilho PF (2021) Charcoal productivity and quality parameters for reliable classification of Eucalyptus clones from Brazilian energy forests. Renew Energy 164:34–45. https://doi.org/10.1016/j.renene.2020.09.057
38. Rivera JEG, Merencio DO, Vistín ASR, Acosta RDL, Espinoza BDC, Abreu-Naranjo R (2022) Thermogravimetric characteristics and kinetic modeling of *Piptocoma discolor* pyrolysis and combustion processes to contribute to its use as a renewable energy source in the Ecuadorian Amazon region. Biomass Convers Biorefin. https://doi.org/10.1007/s13399-021-02178-2
39. Rodrigues T, Braghini Junior A (2019) Charcoal: a discussion on carbonization kilns. J Anal Appl Pyrolysis 143:104670. https://doi.org/10.1016/j.jaap.2019.104670
40. Santos RC, Carneiro ACO, Vital BR, Castro RVO, Vidaurre GB, Trugilho PF, Castro AFNM (2016) Effect of properties chemical and siringil/guaiacil relation wood clones of Eucalyptus in the production of charcoal. Ciência Florestal 26(2):657–669. https://doi.org/10.5902/1980509822765
41. SINDIFER. Sindicato da Indústria do Ferro no Estado de Minas Gerais (2021) Pig iron production in Minas Gerais and in Brazil. Statiscal yearbook reference: 2020. Minas Gerais
42. Surup GR, Trubetskaya A, Tangstad M (2020) Charcoal as an alternative reductant in ferroalloy production: a review. Processes 8(11):1432. https://doi.org/10.3390/pr8111432
43. Telmo C, Lousada J (2011) The explained variation by lignin and extractive contents on higher heating value of wood. Biomass Bioenergy 35(5):1663–1667. https://doi.org/10.1016/j.biombioe.2010.12.038
44. Vos MAE, den Ouden J, Hoosbeek M, Valtera M, de Vries W, Sterck F (2023) The sustainability of timber and biomass harvest in perspective of forest nutrient uptake and nutrient stocks. For Ecol Manage 530:120791. https://doi.org/10.1016/j.foreco.2023.120791

Renewable Energy Sources to Promote Food Sovereignty and Social Inclusion

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Abstract Several examples in the literature and worldwide place biomass as an undervalued fuel, considering that it could have a more noble use than its use in combustion. However, is there anything nobler than eating? Forest biomass is used for cooking food in the wealthiest and most vulnerable social classes as a primary or secondary energy source. For underprivileged families, forest biomass is used in a raw form or with little processing in ineffective energy conversion technologies, which can bring health risks due to long-term exposure. For wealthy families, forest biomass is used with greater use of technology, for example, in densified fuels or efficient ovens and even, in some cases, in preparing "gourmet" foods. Therefore, as it is a

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fuel for the daily use of many populations, forest biomass becomes directly related to food security issues. In addition to participating in broader contexts, forest biomass can promote economic and social development in different locations, enabling food production with added value by families, for example, in rural settlements. Thus, this chapter presents an approach to how other family groups from different social classes use biomass for cooking and maintaining their survival or enjoying exclusive pleasures provided by biomass energy.

Keywords Food security · Sustainable food production · Cooking technologies · Food policy · Clean cooking

1 Introduction

How can we promote using forest biomass in food preparation without harming the environment and people? The answer to this question goes through many dimensions. These issues permeate discussions about food security and sovereignty and broader discussions, such as: economic, social, political, and technological. Thus, it becomes necessary to understand these aspects to use forest biomass for cooking efficiently.

Food and Nutritional Security (FNS) is the realization of everyone's right to regular and permanent access to quality food in sufficient quantity without compromising access to other essential needs, based on health-promoting food policies that respect diversity culturally and that are socially, economically, and environmentally sustainable [74]. It is observed that the FNS concept is a mixture of issues that bring up the challenges of having access to quality food, consuming it in healthy ways, and producing it in sustainable practices.

The conceptualization of FNS is interpreted in different ways around the world. Wealthy countries and large agricultural producers claim to be fighting for their food and nutritional security when they impose barriers to imports and, in this way, increase food prices artificially [72, 152]. On the other hand, in poor or developing countries governed by leaders with a populist position, the concept of Food and Nutrition Security is used to tabulate costs and to establish a villainous image of agricultural producers [107, 110]. With these statements, one arrives at the thought that defining food security is difficult, considering factors ranging from culture and regionality to industrialization and politics. This definition becomes even more complicated when there is a diverse social and cultural panorama, where several peoples and cultures coexist in the same space and, according to the FNS concept, have the same right [13]. In Italy, efforts are to ensure food security and sustainable food production by shifting from conventional to organic farming and encouraging diet changes to reduce meat consumption [92]. In Uganda and Tanzania, efforts are being made to ensure food security through research, development, and agricultural extension for using high-efficiency nitrogen fertilizers in maize crops so that less favored families can access adequate food [42].

To deal with an issue such as Food and Nutritional Security in a country the size of Brazil, considering factors such as the abundance of natural, territorial, and cultural resources, one must first deal with a concept contrary to FNS, the idea of hunger. To define the concept of hunger, dividing a single word into three meanings is necessary. In English, we have three words that can lead to a better understanding: *hunger*, *starvation*, and *famine*. *Hunger* is a desire, a momentary and biological need, and the rich can feel this hunger as much as the poor. *Starvation* is the increase in hunger; it ceases to be individual and becomes collective; we can give the example of students who only eat at school; it is prolonged hunger until a certain point. Finally, *famine* is understood as hunger imposed as a condition on a social group; it is the complete lack of access to food and the means of producing it [84].

In Brazil, there is a belief that the issue of hunger in the country begins in the formation process of Brazilian society, starting in the colonial period. However, on the contrary, it is observed that the first studies on eating habits only began to appear in the nineteenth century (1880–1890), and the first measures to combat hunger were instituted during the Vargas Dictatorship (1937–1945), that is, the political emergency of tackling the scourge of hunger in Brazil was perceived very late, leaving the problem to settle down almost wholly [139]. Nowadays, Federal Government programs aim to establish food security in Brazil in a way adapted to people's social, cultural, and economic reality. The Brazilian federal government, during the term of President Luiz Inácio Lula da Silva, to combat hunger by focusing on its structural causes to guarantee Food and Nutritional Security for Brazilians on three fronts: a set of public policies, the participatory construction of a National Food and Nutrition Security Policy; and a great effort against hunger, involving the three spheres of Government (Federal, State, and Municipal) and all Ministries.

The program's initiatives range from financial aid to the poorest families (with the Bolsa Família card) to the creation of cisterns in the northeastern hinterland, passing through the construction of popular restaurants, instruction on eating habits, distribution of vitamins and food supplements, microcredit loan for poorer families, among others [134]. It should also be mentioned measures that are not directly linked to the issue of Food Security but which have the consequence of providing the poorest regions and those affected by hunger with access and the possibility of changing this reality, such as the transposition of the São Francisco River and construction of roads in the north of the country. Measures like these facilitate food production in areas where there was no production before and contribute to family farming, which many see as the solution to hunger and food insecurity in Brazil.

When discussing the territorial area and cultivable areas, Brazil is undoubtedly interpreted as synonymous with abundance. After all, 851,0345.540 km^2 of extension is a privileged number concerning other countries considered "rich," such as France (55,1695 km^2) and Germany (35,7588 km^2), bringing this to the food production scene. Brazil has 55 million hectares of food grown [62]. However, at the same time as the country deals with super crops and the international recognition of the strength of its power to produce agricultural commodities and food, a significant portion of its people deal with the ghost of hunger, despite Brazil not currently being considered a "poor" country social injustices and the dynamics of the construction process country's economy have contributed to the social problems being experienced by the contemporary Brazilian population [95].

Issues such as land distribution, slavery, European immigration, the unplanned growth of urban areas, lack of access to knowledge, and lack of incentive for those who plant to survive, are problems that link the FNS concept with the concept of food sovereignty [33, 139]. The term sovereignty has a widespread meaning: Superior authority that any other power cannot restrict. Therefore, food sovereignty is connected mainly to the concept of FNS. It is correct to say that the portrait of a country where the two issues are not treated with a singularity is the loss of focus on a primary objective and, consequently, hunger. Although in Brazil, there are model programs that act almost entirely against the issue of Food Insecurity, it is still a challenge to deliver Food Sovereignty to all. Most critics believe it creates a place of passivity and complacency between government and beneficiary since none frees the people from hunger. Whoever kills the need of the people is the government and not the people themselves [7, 34].

Observing history, changes in government, political and cultural bias, between growth and economic setbacks, Food and Nutritional Security in Brazil, and Food Sovereignty is and has been interpreted in different ways over time. However, in all kinds of situational diversity, it has had There is and still is a clear objective, the realization of the right of all to regular and permanent access to quality food, in sufficient quantity, without compromising access to other essential needs, based on health-promoting food policies that respect cultural diversity and that are socially, economically, and environmentally sustainable.

2 Forest Biomass in the World

It is undeniable that biomass is one of the most important fuels for cooking. Yet, according to the [149], about 2.4 billion people still lack access to clean cooking technologies. Forest biomass for household use generally comes in the following forms: firewood, charcoal, briquettes, and pellets. Their use cuts across all social classes, from the poorest to the richest [5, 133].

Firewood is the raw form of wood and requires less technology. Therefore, it is used primarily in South America, sub-Saharan Africa, and South Asia for cooking over open fires and low-technology stoves [16, 79, 86]. Another way to use firewood is to prepare food in bakeries and pizzerias [77] or in restaurants to prepare grilled and smoked food [101, 122].

Charcoal can be produced from forest biomass through the pyrolysis process and has about twice the calorific value of raw wood [115]. As firewood, charcoal is used for grilling and smoking food, especially in countries in South America and sub-Saharan Africa [88, 97]. Families in developing countries also use charcoal for heating and lighting [109].

Forest biomass is the raw material for producing briquettes and pellets through a densification process. The result is a fuel with more homogeneous particle sizes, high heating value, and low greenhouse gas and particulate emissions [26, 50, 124]. Briquettes and pellets undergo a more technological manufacturing process. They require more efficient stoves for combustion, which is why they are more commonly used in developed countries in North America, Europe, and China [45, 90, 105]. Generally, pellets and briquettes are usually used to heat and light homes because they have a high heating value, more controlled combustion, and low gas emissions [85, 144].

We can understand that people widely use forest biomass to meet their cooking, heating, and lighting needs. Firewood is most used for cooking and is common among both the poorest and wealthiest segments of the population. Charcoal is also used primarily for cooking at home. Still, it is less common compared to firewood because it must go through a pyrolysis process. Briquettes and pellets are the least used forest biomass fuels because they must undergo a densification process and require more technically sophisticated stoves, primarily in European and North American countries.

3 What Does Forest Biomass Mean for Households?

Forest biomass is one of the renewable energy sources. With wind, water, solar, geothermal, and ocean energy, it is essential to transition away from the fossil-fuel-based global economic model. Today, the production of heat, electricity, fuels, chemicals, and other petroleum-based materials contributes to climate change by releasing greenhouse gases (GHGs) and deficits in carbon sequestration. In this context, we face increasing pressure on natural ecosystems, changing land-use patterns, intensive agriculture, biodiversity loss, and energy crisis [112]. In addition, extreme weather events are likely to become more frequent [63], and human and non-human populations face heat waves, storms, floods, and droughts. This results in losses in agricultural productivity, generating food shortages and favoring population displacement, promoting numerous conflicts [127]. In general, the use of forest biomass among renewable sources can mitigate environmental impacts because it does not alter the carbon cycle in the long term and helps optimize CO_2 levels in the atmosphere [14]. It is also a feedstock for local and decentralized businesses, helping to reduce dependence on fossil fuels [142]. In addition, research on vegetable biomass is diverse and has recently been summarized. Among the possible uses are conversion into biofuels or bioproducts and electricity generation [119].

Moreover, what is biomass? It is a biological and renewable material derived from living or recently dead organisms, including plants and animals. There are two typical applications of the term. The first refers to the ecological sense of biomass, which usually indicates the carbon stock of ecosystems from living or dead matter below or above ground [47]. The second relates to energy practices, including traditional heat production for cooking, domestic heating, modern conversion to biofuels, and combined heat and power generation [65]. Biomass of plant origin has a broad scope, as it comprises materials formed through photosynthesis or generated in its use [19], including wood and firewood, energy crops, charcoal, agroforestry, rural, industrial, domestic, and commercial waste (Fig. 1).

In this context, we can classify it as a heterogeneous raw material. Moreover, forest biomass is distributed in different spaces and times, so its volume and characteristics are influenced by local climatic and geographic factors [142]. Therefore, production,

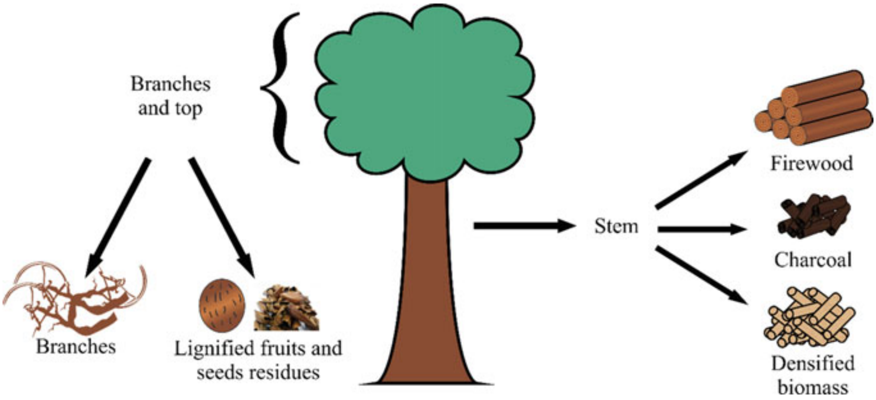

Fig. 1 Possibilities for using forest biomass (*Source* The authors 2023)

stock, and transport data are essential in building a forest biomass production chain [54]. Thus, regional solutions for biomass use for energy are thought in countries from the south [18, 59] to the global north [48, 58, 99].

Humanity has always had its socioeconomic progress linked to using biomass for energy. However, the separation between traditional and modern use, or bioenergy, has opened space to depreciate biomass for such a noble purpose as cooking. Cooking is a necessary process for humankind. Proper cooking techniques make food more digestible and increase food's bioavailability and flavor [69]. It is further estimated that raw or unprocessed biomass and charcoal in cooking food occur in 39.5% of households worldwide [147, 148]. However, this high number is affiliated with reality in emerging and developing countries [116]. In these nations, large populations use energy sources that contribute to household air pollution by emitting carbon monoxide (CO) and particulate materials [98]. The term clean cooking refers to the use of efficient fuels or equipment inside homes, seeking a lower emission of pollutants. According to the WHO Global Air Quality Guidelines [148], emissions should meet the annual average air quality guideline level (AQG, 5 μg m^{-3}) or the Interim Target-1 level (IT1, 35 μg m^{-3}) for $PM_{2.5}$, and either the 24-h average air quality guideline level (AQG, 4 mg m^{-3}) or the Interim Target-1 level (IT-1, 7 mg m^{-3}) for CO [148]. As WHO [146] described, solar-based, electric cooking systems that use biogas, natural gas, liquefied petroleum gas (LPG), or alcohol fuels, including ethanol, are considered clean. Solid fuels can also fall into this category, provided they meet adequate levels confirmed in laboratory tests following an international laboratory testing protocol.

Expanding access to clean cooking is a strong ally for advances in at least 5 of the United Nations (UN) Sustainable Development Goals (SDGs), these being (3) Good health and well-being, (5) Gender equality, (7) Affordable and clean energy, (13) Climate action, (15) Life on land [118]. When forcing on SDG 7, which aims at universal provision of modern, reliable, and affordable energy services by 2030, including services of electricity and clean cooking facilities, we notice progress over time. However, the historical series given by the World Health Organization [150] indicates a slow pace of growth, not compatible with the targets set. Hence, there is a double question, one of technical nature and the other of social interest: are there efficient ways to use traditional biomass for cooking food for these populations? At the same time, are there ways to mitigate the effects of domestic air pollution? Finally, having overcome these material questions, what is the role of biomass in the food security of these populations?

4 Forest Biomass in Food Preparation by Different Socioeconomic Classes

In addition to carbon–neutral products and energy, the appropriate use of forest biomass is necessary to develop robust production models that transform linear production chains into circular ones. Thus, we could advance the transition to a circular economy [76] and strengthen the United Nations' 17 SDGs, which aim to motivate and facilitate the world's economies to address serious social and environmental problems. In practice, products necessary for modern life could be from renewable sources. Therefore, it is common that biomass applications such as sophisticated biofuels and other bioproducts are always required and encouraged. However, the traditional use of biomass in food preparation is given low prominence in socioeconomic and technical studies. It is even treated as a less noble material that needs to be avoided because it offers health risks (Fig. 2).

There are examples of studies that prove the association of the use of biomass for cooking with symptoms of depression and anxiety in the elderly [37], loss in cognitive

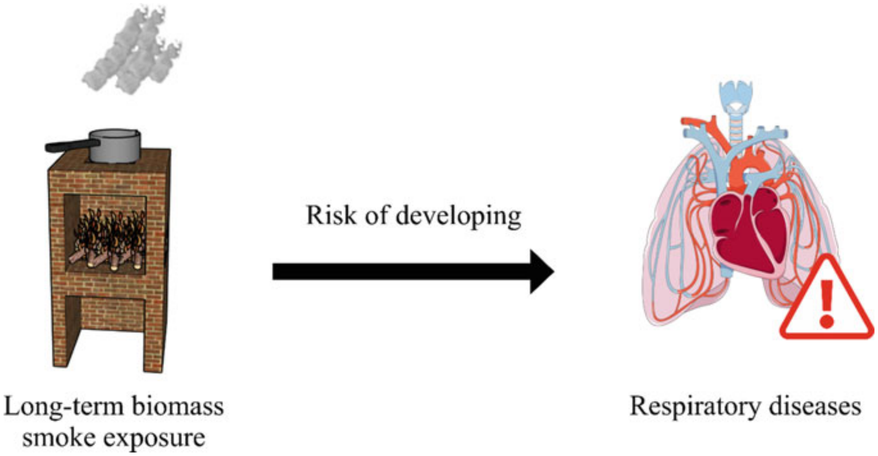

Fig. 2 Exposure to biomass smoke may increase the risk of developing respiratory diseases (*Source* The authors 2023)

skills in children up to 4 years old [83], with respiratory health risks in pregnant women [138] and even consequences with pre-menopausal depression [10]. Such cited researches are naturally observational, so they compared different populations and investigated a sole factor: the employment of biomass in households. There is robustness in this type of verification, and we can obtain data without purposely subjecting people to a risk factor for their health. In this sense, it is necessary to remember that populations that use biomass are often poor and dependent on its frequent use for food.

By 2020, sub-Saharan Africa and South Asia countries culminated in the list of nations with the lowest share of the population with access to clean cooking fuels and technologies [147]. People in these countries are also more likely to be deprived of adequate nutrition, sanitation, housing, or access to clean water and electricity [136]. Thus, we must consider that poverty brings with it personal material disadvantages, systemic and environmental constraints, daily experiences of stress, cognitive demands, and situations of scarcity that together act to worsen people's health [6], with the use of biomass for cooking being one more conditioning factor among them. There is a technical bias that transforms traditional biomass into a more efficient biofuel. At the same time, it is possible to modify the conditions of a household and its equipment to receive this energy source for cooking food without serious emissions of pollutants. Thus, we must understand that forest biomass is a potential source and instrument of an energy chain that should be broad and diverse. With it, we can start an integrated approach to overcome the systemic deprivations conditioned to the lower social classes, in which policies for improving conversion systems into biofuels and domestic equipment with low pollutant emissions are included.

Another relevant context is utilizing forest biomass as an alternative and not exclusive fuel in food preparation. In these cases, the use of charcoal is ordinary in food preparation due to the characteristics it gives to food in terms of flavor and texture [141]. In South American countries such as Brazil and Argentina, charcoal takes center stage in specific preparations: the barbecue [28, 43]. This is a combination of the culinary techniques of the native peoples with beef obtained from the cattle raising implemented by the colonizers [52]. For similar purposes, firewood, briquettes, and pellets can still be found in markets in the USA, European Union, Australia, and Japan [68, 128]. Such cited fuels will be explored in the following session.

Thus, going beyond the limits of food security for homes, forest biomass is also fuel for the culinary tradition. It helps food to become an object of adequate consumption by attributing physicochemical characteristics and flavor through the interaction of ingredients and preparation techniques. In addition to corroborating with the maintenance of a symbolic purpose, food is also appreciated because of the socially attributed values or the relationships that can be established in its consumption [52]. Finally, it is crucial to understand that the preferences of fuel for cooking food have as background the socioeconomic and cultural aspects of the populations.

5 Conversion of Forest Biomass into Clean Energy for Cooking

5.1 *Solid Biofuels to Replace Traditional Firewood*

Densification is the first example of technology to generate modern and efficient solid biofuels. It is a biomass compaction process that allows the production of a new product with higher apparent density than the raw material that originated it. Its application in residual biomass is common, bringing as an advantage the energy use associated with the reduction of deforestation for the removal of firewood and the use of renewable sources for fuels [135]. Densification occurs under different operating conditions of temperature and pressure, in natural binders' presence exclusively or not [17]. The type of biomass used influences the production parameters employed. In general, the compaction pressure creates plastic and elastic deformities that reduce the voids between particles, favoring the mechanical strength of the biofuel [106] and the energy increment [111]. Temperature acts by modifying lignin and extractives to the plastic condition, which is necessary for the connection and adhesion of biomass particles [24, 71]. Under these conditions, the binding agents inherent in biomass (e.g., lignin, starch, and proteins) corroborate with interparticle adhesion. However, adding binders may be necessary [123]. Densification is integrated with preparation steps, which may include drying, biomass reduction, and grading of the particles obtained.

In general, we can obtain two different products in the form of briquettes or pellets. Both have higher volumetric energy concentration, lower humidity, and homogeneity than the source feedstock [51]. The dimensions of pellets vary between 6 and 16 mm. At the same time, briquettes have diameters starting at 50 mm, varying according to market demand or standards [38]. Both products are direct substitutes for wood in furnaces, heaters, and boilers. According to FAO [96], pellets are the forest biomass fuels with the greater economic importance globally, moving approximately 4.4 billion dollars in imports and exports. The same authors estimated that the production and consumption of pellets worldwide increased by 49% and 41%, respectively, between 2016 and 2020.

The use of these biofuels in domestic furnaces has been the subject of research. In Nigeria, briquettes produced with corn cob and bark of palm oil trunks showed suitable thermal properties for combustion and GHG emissions aligned with environmental standards [78]. Studies in Uganda have emphasized that household use of briquettes made from rice husks, coffee, and binders translates into energy savings [93]. In the Bolivian context, briquettes with waste cardboard and sawdust showed better performance through environmental Life Cycle Assessment (LCA) within a 100–130 km radius of the production plant, being superior to all fossil fuels used in Andean areas for heating and cooking food [44]. Finally, we point out that replacing raw biomass with briquettes can benefit health. This was indicated by the research of [108], elucidating the similarities and differences in $PM_{2.5}$ (particulate matter with diameter $\leq 2.5\ \mu$m) emissions and cytotoxicity between these two fuels. The emission characteristics of briquettes decrease inflammatory response and cell membrane damage, which contributes to reducing adverse pulmonary effects. In this context, studies that perform on-site analysis of densified fuels associated with traditional and efficient kilns are still required.

Furthermore, thermochemical processes can convert biomass into another biofuel suitable for a domestic environment without pollution if they meet the above recommendations. The pyrolysis or carbonization of woody materials occurs in high-temperature environments with low presence or absence of oxygen, and its main product is charcoal. This material is rich in carbon and has higher specific energy, resulting from removing water and other volatile compounds [41]. However, we can tense a debate about using environmentally and socially responsible sources of charcoal production. In sub-Saharan African countries such as Ghana, charcoal activity results in vegetation loss and ecological impacts while meeting household energy needs, supporting the livelihoods of different social groups, and transforming local economies [2]. In this sense, there are social risks to extinguishing charcoal production. However, it is recommended to incorporate interventions such as switching from the more efficient production models that earth mound for charcoal production, given that producers are flexible in adapting to any new technology indicated [8]. For [12] decision-makers should look at production methods, creating policies to make it economically viable and environmentally friendly, especially to reduce GHG emissions. A similar narrative is supported by [70], who indicated that this conversion technology is a valuable tool in the energy diversification process in Mozambique. Even though these same authors raise questions about applying laws disfavoring already weakened social groups that depend on coal for subsistence activities, finally, local and context-specific planning and evaluation should be considered for projects that aim at rural development so that the actors and stakeholders can contribute to the process and the production cycle [57].

In Brazil, in a different context from the production for homes and subsistence purposes, authors have indicated that the substitution of traditional kilns by the furnace-kiln system (Fig. 3) has shown excellent performance in reducing the emissions of pollutants, following the targets established by international agreements [120].

As for the source of woody material, this can also be diversified and thus mitigate pressures on native biomes. Studies in the Brazilian Amazon, as seen in Chap. 4 of this book, indicate that using residues from forest harvesting activities can supply domestic systems with quality charcoal [88]. Furthermore, due to the great diversity of residues, it is also possible to control the carbonization process in brick kilns to obtain a high-quality product [87]. Pruning residues are other potential sources of charcoal in nearby or urban areas [102].

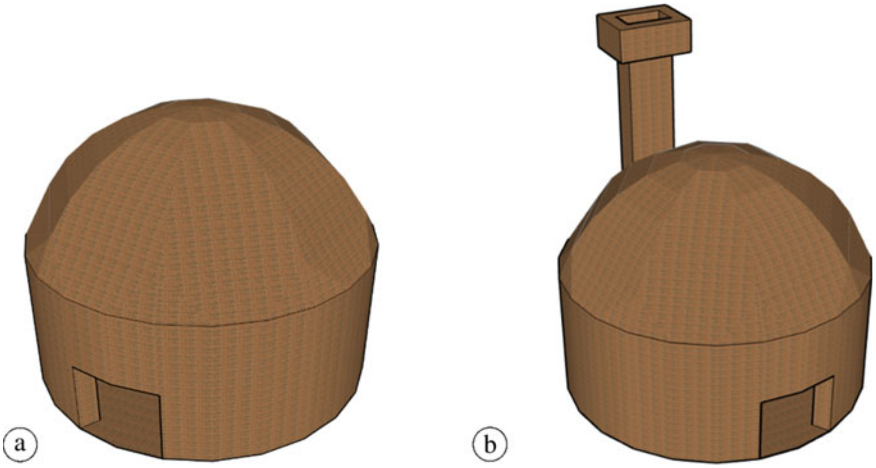

Fig. 3 Types of kilns for charcoal production, where: **a** traditional kiln; **b** furnace-kiln system) (*Source* [120])

5.2 Gaseous Biofuels Replacing Cooking Gas

Households with access to clean cooking facilities have increased in recent years in favor of liquefied petroleum gas (LPG). According to the International Energy Agency [64], this fuel is essential to significantly reduce indoor air pollution, bringing health benefits to several households. Crucial policy instruments for this reality involve informing about the LPG market and clarifying the consequences of using traditional biomass for cooking [66]. Alternatively, biogas fulfills the function of clean fuel, with a smaller carbon footprint and not dependent on fossil sources. It is a product of the biochemical conversion of biomass in an anaerobic environment. The elements that makeup biogas are primarily composed of methane (CH_4) in a proportion ranging from 50 to 75%, along with carbon dioxide (CO_2), which comprises 25–50% of the composition [55]. Small amounts of other gases, such as oxygen (O_2), hydrogen sulfide (H_2S), nitrogen (N_2), and water vapor, are also present. In addition, biogas can be converted into biomethane using techniques to purify CH_4 and recover CO_2 simultaneously [89], which is employed in industry for various purposes.

Biogas from household digesters could improve the standard of living of families. In rural areas, this biogas contributes to reducing fuel costs and time to collect firewood, besides mitigating $PM_{2.5}$ emissions in the domestic environment [113]. We emphasize that its use applies to homes with sufficient outdoor space to store the equipment. In this context of rural homes, LPG usually has higher costs due to supply logistics, transportation, and storage requirements [60]. In this sense, biogas can contribute to the energy transition of cooking fuels in areas with land availability and near the feedstock. It is necessary to (i) overcome technologies poorly adapted to local conditions, (ii) overcome barriers to financing facilities [125], (iii) study available biomass; and (iv) manage waste professionally and in the long term [91]. Sound policies focusing on the environmental and social benefits of biogas are demanded that will contribute to this paradigm shift. Case studies of measures to expand and democratize LPG has already been employed in emerging countries [15, 75] and can be adapted to a reality of mitigating climate change and improving social factors.

5.3 Efficient Equipment for Cooking Food

Traditional stoves using raw/unprocessed biomass have low energy efficiency and high pollutant emissions due to their rudimentary structure [36]. Some geometric configurations of the stove are essential, all of which will affect the efficiency of the biomass burning, the combustion gases, and consequently, the energy that reaches the pot with the food [104]. During biomass combustion in traditional stoves, heat is released diffusely. However, the optimal is to concentrate this energy in a single direction, allowing food cooking with less fuel [94]. Thus, a combustion chamber is necessary, in adequate proportions, and made of material that limits energy loss to the environment. The size of combustion chambers will also affect energy efficiency [36]. So larger heights favor the reaction time of the combustion gases with oxygen, releasing more heat into the system. However, there are limits so that the height does not affect the flame temperature, which is responsible for heating the pots used to cook the food. In the study by [61], the ideal measurements for the combustion chamber of 16 cm in height and 13 cm in diameter were obtained through modeling.

Another critical component of an efficient stove is the chimney. Its existence mitigates the emissions of particles and pollutants in the indoor environment, favoring people's health [82]. Moreover, it dictates the stove's power supply since it tends to change the gas temperature and the combustion efficiency [114]. It is worth clarifying that excess air is mandatory in complete combustion [35, 143]. Therefore, building systems that favor airflow is appropriate, as this burns the biomass and gains in convective heat transfer [4]. However, care must be taken with high airflow. The combustion gases are expected to be removed from the system with improving energy efficiency, instead, it only favors biomass consumption [67].

The biomass source used will also modify the efficiency of the stove, as well as its layout, size, moisture content, and heating value. [94] Therefore, in practice, only some models can replace traditional stoves. It is valid to ensure suitable configurations for different stoves and families according to their needs [80]. So, the uptake of efficient stoves by poorer populations occurs through programs that consider people's preferences. Experiments show that stove dissemination rates are low when these factors are ignored and programs fail [40]. Finally, it should be remembered that efficient equipment is no long-term substitute for universal access to affordable, reliable, and modern energy services.

6 Promoting the Sustainable Use of Forest Biomass

In addition to security and food sovereignty issues, promoting forest biomass with low environmental and human health impacts also involves economic, social, political, and technological discussions.

From an economic perspective, using forest biomass is a cost-effective way to obtain energy for cooking food because it is a fuel that can be easily found anywhere in the world and can often be obtained from nature without much effort [16]. The use of raw biomass in the form of firewood is usually associated with low-income families who do not have access to another energy source for cooking and rely on obtaining wood from the nearest forest for survival [100, 101]. The data on the use of forest biomass for cooking can be alarming when we put them in context, such as in two large emerging economies, Brazil and India, where about 25% and 50% of households, respectively, rely on fuelwood [53, 75]. Indiscriminate use of forest biomass for cooking can cause problems such as high gas emissions, suppression of native vegetation, and loss of biodiversity. However, public policies, technological development, and financial incentives for properly using forest biomass can restrain this practice.

From a social perspective, using biomass may be based on regional or cultural reasons, making the transition from raw biomass to cleaner energy sources challenging. Most families that use forest biomass inefficiently to cook food live either in remote regions or on the outskirts of cities and are usually composed of poor people [56, 96, 131]. The geographic location of this population is often a determining factor in the choice of energy source used for cooking, so the closest option is firewood [1, 101]. Another social aspect of using forest biomass for cooking is the culture of a particular population. Often the preparation way of food is passed down from generation to generation, so the use of this energy source continues. In the case of Brazil, grilling is a food embedded in the country's culture, and the most common energy source used is charcoal, which directly affects the outcome of the meal [39, 103]. Thus, the social aspect is essential in promoting the sustainable use of forest biomass.

From a political perspective, the use of forest biomass should be encouraged by public actions in the form of laws, either reducing the social insecurity of people who need to use this source of energy or creating protection mechanisms against the exploitation of native forests and for the implementation of forests for energy purposes. The uncontrolled extraction of wood can lead to the destruction of ecosystems, soil deterioration, and change of ownership of watercourses, among others [1, 137]. Many countries have laws that combat illegal logging. However, more than enforcement is needed to prevent environmental impacts [11, 121, 140]. In China, there are public policies that aim at the transition from the use of traditional biomass to the use of modern biomass in rural homes [29, 151]. In Ethiopia, public policy development focuses on educating rural households about using biomass and more efficient cooking equipment [73]. In Brazil, the National Biofuels Policy presents as one of its foundations the importance of adding value to biomass as a form of environmental preservation and promotion of development and economic and social inclusion [22]. In developing countries such as Brazil, Nepal, and Ethiopia, the use of forest biomass is linked to the collection distance, in which low-income families prefer to use the closer material [49, 83, 126]. In developed countries such as Portugal, Italy, and Germany, the use of forest biomass is regulated by more specific norms, mainly regarding the technical characteristics of the fuel and the cooking technology [129]. Another point to be addressed politically is creating social assistance mechanisms that allow the poorest population to use forest biomass for cooking more efficiently.

From a technological perspective, the use of forest biomass can be improved on two points: (I) technologies for burning with greater thermal efficiency and (II) more efficient forest-based fuels. More efficient cooking appliances provide lower greenhouse gas (GHG) emissions and greater energy efficiency so that human exposure to harmful gases is reduced and the fuel needed is lower [20, 130]. The emission of GHG, nitrous oxides (NO_X), polycyclic aromatic hydrocarbons (PAHs), and particulate matter from the inefficient burning of biomass can generate serious problems for public health and the environment [21, 145]. Another critical point that can be approached from a technological perspective to encourage the use of forest biomass for cooking is the development of more efficient fuels through physical–mechanical or thermochemical routes. Concrete evidence suggests biomass densification techniques can increase its physical properties and energy efficiency [9, 27, 36]. Briquettes and pellets are the most common forms of densified biomass. The main characteristics that make them more efficient than firewood are higher energy density, a lower percentage of moisture, a better combustion rate, and lower emission of particulate matter [25, 81].

In addition to densification processes, there are also thermochemical routes for improving forest biomass for cooking, such as torrefaction and pyrolysis. Torrefaction is a thermochemical process that aims to improve the characteristics of biomass, taking place in an environment lacking or with little oxygen at temperatures ranging between 200 and 300 °C [30, 96]. Pyrolysis is a thermochemical process that aims at the complete transformation of forest biomass into new products: charcoal, pyroligneous liquid, and non-condensable gases, occurring at temperatures above 350 °C, with heating rates and residence time in the reactors varying depending on the type of pyrolysis [31, 32]. As it is a process that depends on technology, the pyrolysis product commonly used for cooking is charcoal, as it does not need any treatment after production [3, 15, 23]. Charcoal is a fuel that may have its origin in forest biomass. It has some characteristics superior to firewood, such as higher calorific value, less volatile materials, and higher energy density [39, 115]. In domestic environments, charcoal is used in stoves or barbecues with low technology employed, usually without a ventilation system (Fig. 4a) [117].

On the other hand, steakhouses, pizzerias, or restaurants use charcoal to prepare “gourmet” dishes with high added value in ovens with an exhaust system and liquid collection (Fig. 4b). Therefore, the use of charcoal as a source of energy for cooking permeates all social classes, from less favored families in rural areas to families with greater purchasing power in urban centers. In this way, developing technologies for

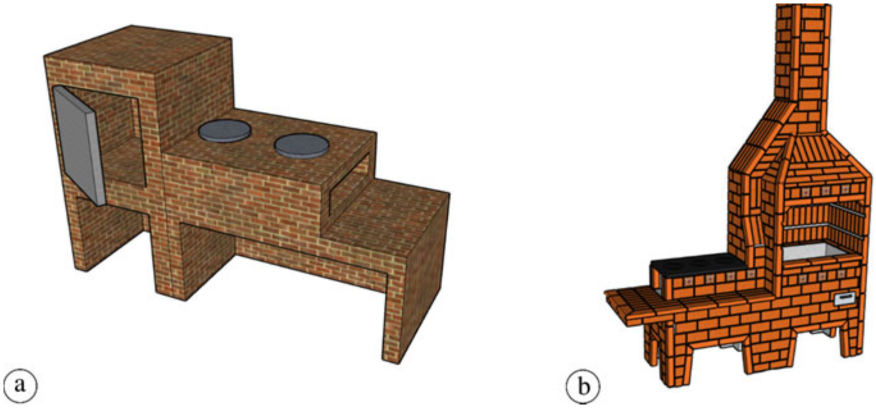

Fig. 4 Illustration of ovens for cooking food in which: **a** rural oven with low technology, without air circulation system and liquid collection; **b** oven in a commercial environment, with an exhaust system and collection channels (*Source* The authors 2023)

stoves and forest biomass fuels can guarantee access to more efficient renewable energy sources for cooking food.

Therefore, understanding the economic, social, political, and technological perspectives can sustainably promote the use of forest biomass to ensure its ecologically correct, socially just, and economically viable use. In this way, it contributes to developing food sovereignty in countries. Furthermore, it provides the population's food security by promoting the efficient use of forest biomass in the household energy matrix.

7 Conclusions

In a world with frequent discussions about food distribution, public policies, and sustainability, the role of people, governments, and non-governmental entities becomes more evident when solving these problems directly bound to human survival. This chapter addressed concerns about how food security and food sovereignty are correlated and what actions all actors involved can take to produce, consume, and distribute food sufficiently and fairly without negatively affecting future generations. Another point addressed was how families from different social classes relate to forest biomass in food preparation. There is the perception that wealthier families are more likely to achieve cleaner and more efficient cooking technologies. However, in comparison, poorer families use natural forest fuel in more rustic equipment, generating public health problems. Thus, to mitigate this food inequality, public policies are needed to expand the access of poorer people to more efficient cooking technologies and the development of equipment and fuel that are cheaper and simpler to use. Only then will a food transition be possible for less favored peoples, allowing access to food in an economically viable, environmentally correct, and socially just way.

References

1. Abdu N, Tinch E, Levitt C, Volker PW, Hatton MacDonald D (2022) Illegal firewood collection in Tasmania: approaching the problem with the Institutional Analysis and Development (IAD) framework. Land use policy 118. https://doi.org/10.1016/j.landusepol.2022.106130
2. Ablo AD, Osei L, Jarawura FX, Yaro JA (2022) Sacrificing the savannah woodlands for energy and livelihoods? Charcoal production in Ghana. Energy Sustain Dev 70:549–559. https://doi.org/10.1016/j.esd.2022.09.001
3. Abreu MW, Ferreira DV, Pereira AO, Cabral J, Cohen C (2021) Household energy consumption behaviors in developing countries: a structural decomposition analysis for Brazil. Energy Sustain Dev 62:1–15. https://doi.org/10.1016/j.esd.2021.03.001
4. Agenbroad J, DeFoort M, Kirkpatrick A, Kreutzer C (2011) A simplified model for understanding natural convection driven biomass cooking stoves—Part 2: With cook piece operation and the dimensionless form. Energy Sustain Dev 15(2):169–175. https://doi.org/10.1016/j.esd.2011.04.002
5. Antar M, Lyu D, Nazari M, Shah A, Zhou X, Smith DL (2021) Biomass for a sustainable bioeconomy: An overview of world biomass production and utilization. Renew Sustain Energy Rev 139
6. Appelhans BM (2023) The cognitive burden of poverty: a mechanism of socioeconomic health disparities. Am J Prev Med 64(2):293–297. https://doi.org/10.1016/j.amepre.2022.08.012
7. Aranha AV (2010) Fome Zero - Uma História Brasileira
8. Asare F, Owusu FW, Gazo R (2022) Sustainable charcoal production drive in rural communities in Ghana, West Africa. Energy Sustain Dev 68:364–372. https://doi.org/10.1016/j.esd.2022.04.013
9. Bajwa DS, Peterson T, Sharma N, Shojaeiarani J, Bajwa SG (2018) A review of densified solid biomass for energy production. Renew Sustain Energy Rev 96:296–305
10. Banerjee M, Siddique S, Dutta A, Mukherjee B, Ranjan Ray M (2012) Cooking with biomass increases the risk of depression in pre-menopausal women in India. Soc Sci Med 75(3):565–572. https://doi.org/10.1016/j.socscimed.2012.03.021
11. Bär R, Reinhard J, Ehrensperger A, Kiteme B, Mkunda T, Wymann von Dach S (2021) The future of charcoal, firewood, and biogas in Kitui County and Kilimanjaro Region: scenario development for policy support. Energy Policy 150. https://doi.org/10.1016/j.enpol.2020.112067
12. Bekele B, Kemal AW (2022) Determents of sustainable charcoal production in AWI zone; the case of Fagita Lekoma district Ethiopia. Heliyon 8(12):e11963. https://doi.org/10.1016/j.heliyon.2022.e11963
13. Belik W (2003) Perspectivas para segurança alimentar e nutricional no Brasil Prospects for food and nutricional safety in Brazil. Saúde e Sociedade 12(1):12–20
14. Benebere P, Appiah DO, Aabeyir R, Abass K, Guodaar L (2023) Climate change mitigation potential of agroforestry farms in West African Savanna. Environ Challenges 10:100678. https://doi.org/10.1016/j.envc.2023.100678
15. Bezerra P, Cruz T, Mazzone A, Lucena AFP, De Cian E, Schaeffer R (2022) The multidimensionality of energy poverty in Brazil: a historical analysis. Energy Policy 171:113268. https://doi.org/10.1016/j.enpol.2022.113268
16. Bharadwaj B, Pullar D, To LS, Leary J (2021) Why firewood? Exploring the co-benefits, socio-ecological interactions and indigenous knowledge surrounding cooking practice in rural Nepal. Energy Res Soc Sci 75. https://doi.org/10.1016/j.erss.2021.101932

17. Bhattacharya SC, Sett S, Shrestha RM (1989) State of the art for biomass densification. Energy Sour 11(3):161–182. https://doi.org/10.1080/00908318908908952
18. Bowd R, Quinn NW, Kotze DC, Guilfoyle MJ (2018) A systems approach to risk and resilience analysis in the woody-biomass sector: a case study of the failure of the South African wood pellet industry. Biomass Bioenerg 108:126–137. https://doi.org/10.1016/j.biombioe.2017.10.032
19. Brand MA (2010) Energia de biomassa florestal. Editora Interciência, Rio de Janeiro
20. Brandelet B, Rose C, Landreau J, Druette L, Rogaume Y (2021) Toward a cleaner domestic wood heating by the optimization of firewood stoves? J Clean Prod 325. https://doi.org/10.1016/j.jclepro.2021.129338
21. Brandelet B, Rose C, Rogaume C, Rogaume Y (2018) Impact of ignition technique on total emissions of a firewood stove. Biomass Bioenergy 108:15–24. https://doi.org/10.1016/j.biombioe.2017.10.047
22. Brasil (2017) Política Nacional de Biocombustíveis (RenovaBio). Presidência da República. Disponível em: https://www.planalto.gov.br/ccivil_03/_ato2015-2018/2017/lei/l13576.htm. Acesso em: 07 mar 2023
23. Broto VC, Arthur FSRM, Guibrunet L (2020) Energy profiles among urban elite households in Mozambique: Explaining the persistence of charcoal in urban areas. Energy Res Soc Sci 65. https://doi.org/10.1016/j.erss.2020.101478
24. Cao Z, Zhang S, Huang X, Liu H, Sun M, Lyu J (2020) Correlations between the compressive strength of the hydrochar pellets and the chemical components: evolution and densification mechanism. J Anal Appl Pyrol 152:104956. https://doi.org/10.1016/j.jaap.2020.104956
25. Carter E, Shan M, Zhong Y, Ding W, Zhang Y, Baumgartner J, Yang X (2018) Development of renewable, densified biomass for household energy in China. Energy Sustain Dev 46:42–52. https://doi.org/10.1016/j.esd.2018.06.004
26. Cen K, Chen F, Chen D, Gan Z, Zhuang X, Zhang H (2022) Life cycle assessment of torrefied cornstalk pellets combustion heating system. Fuel 320. https://doi.org/10.1016/j.fuel.2022.123968
27. Cencin A, Zanetti M, Urso T, Crivellaro A (2021) Effects of an innovative densification process on mechanical and physical properties of beech and Norway spruce veneers. J Wood Sci 67(1). https://doi.org/10.1186/s10086-021-01948-w
28. Champredonde M (2008) The source and market development of a premium product—beef from the Argentine Pampas. Meat Sci 79(3):534–540. https://doi.org/10.1016/j.meatsci.2007.10.021
29. Chen Q, Yang H, Liu T, Zhang L (2016) Household biomass energy choice and its policy implications on improving rural livelihoods in Sichuan, China. Energy Policy 93:291–302. https://doi.org/10.1016/j.enpol.2016.03.016
30. Chen WH, Peng J, Bi XT (2015) A state-of-the-art review of biomass torrefaction, densification and applications. Renew Sustain Energy Rev 44:847–866
31. Chen X, Che Q, Li S, Liu Z, Yang H, Chen Y, Wang X, Shao J, Chen H (2019) Recent developments in lignocellulosic biomass catalytic fast pyrolysis: strategies for the optimization of bio-oil quality and yield. Fuel Process Technol 196
32. Choi YS, Lee KH, Zhang J, Brown RC, Shanks BH (2015) Manipulation of chemical species in bio-oil using in situ catalytic fast pyrolysis in both a bench-scale fluidized bed pyrolyzer and micropyrolyzer. Biomass Bioenergy 81:256–264. https://doi.org/10.1016/j.biombioe.2015.07.017
33. Chonchol J (2005) A soberania alimentar. Estudos Avançados 19(55):33–48. https://doi.org/10.1590/S0103-40142005000300003
34. de Freitas Coca EL, Santos LLM, Souza RDP, Salvaterra JR (2020) A soberania alimentar na Geografia Agrária brasileira. Terra Livre 1(54):586–615
35. Deng M, Li P, Shan M, Yang X (2020) Optimizing supply airflow and its distribution between primary and secondary air in a forced-draft biomass pellet stove. Environ Res 184:109301. https://doi.org/10.1016/j.envres.2020.109301

36. Deng M, Zhang P, Yang H, Ma R (2023) Directions to improve the thermal efficiency of household biomass cookstoves: A review. Energy Build 278:112625. https://doi.org/10.1016/j.enbuild.2022.112625
37. Deng Y, Gao Q, Yang T, Wu B, Liu Y, Liu R (2021) Indoor solid fuel use and incident arthritis among middle-aged and older adults in rural China: a nationwide population-based cohort study. Sci Total Environ 772:145395. https://doi.org/10.1016/j.scitotenv.2021.145395
38. Dias, JMCS, Souza DT, Braga M, Onoyama MM, Miranda, CHBM, Rocha JD (2012) Produção de briquetes e péletes a partir de resíduos agrícolas, agroindustriais e florestais. Embrapa Agroenergia, Brasília
39. Dias Júnior AF, Andrade CR, Milan M, Brito JO, de Andrade AM, de Souza ND (2020) Quality function deployment (QFD) reveals appropriate quality of charcoal used in barbecues. Sci Agric 77(6). https://doi.org/10.1590/1678-992x-2019-0021
40. Ekouevi K, Tuntivate V (2012) Household energy access for cooking and heating: lessons learned and the way forward. A World Bank study. World Bank, Washington, DC. Available in: http://hdl.handle.net/10986/9372. Accessed 08 Mar 2023
41. El Bassam N (2021) Energy resources, global contribution, and applications. In: Distributed renewable energies for off-grid communities. Elsevier, pp 165–211
42. Falconnier GN, Leroux L, Beillouin D, Corbeels M, Hijmans RJ, Bonilla-Cedrez C, van Wijk M, Descheemaeker K, Zingore S, Affholder F, Lopez-Ridaura S, Malézieux E, Makowski D, Rurinda J, van Ittersum MK, Vanlauwe B, Giller KE, Lammoglia SK, Waha K (2023) Increased mineral fertilizer use on maize can improve both household food security and regional food production in East Africa. Agric Syst 205. https://doi.org/10.1016/j.agsy.2022.103588
43. Fernandes AM, Teixeira OS, Revillion JP, Souza ÂRL (2022) Beef as a socio-cultural identity: Rural and urban consumers' attitudes from Rio Grande do sul, Brazil, facing cultured beef. J Rural Stud 95:438–448. https://doi.org/10.1016/j.jrurstud.2022.09.035
44. Ferronato N, Baltrocchi APD, Romagnoli F, Calle Mendoza IJ, Gorritty Portillo MA, Torretta V (2023) Environmental life cycle assessment of biomass and cardboard waste-based briquettes production and consumption in Andean areas. Energy Sustain Dev 72:139–150. https://doi.org/10.1016/j.esd.2022.12.005
45. Ferronato N, Calle Mendoza IJ, Ruiz Mayta JG, Gorritty Portillo MA, Conti F, Torretta V (2022) Biomass and cardboard waste-based briquettes for heating and cooking: thermal efficiency and emissions analysis. J Clean Prod 375. https://doi.org/10.1016/j.jclepro.2022.134111
46. Food and Agriculture Organization of The United Nations—FAO (2022) FAO yearbook of forest products. FAO, Rome. https://doi.org/10.4060/cc3475m
47. Food and Agriculture Organization of The United Nations—FAO. Global Forest Resources Assessment 2020. FAO, Rome. www.fao.org/forestry. Accessed 5 Jan 2023
48. Furubayashi T, Nakata T (2021) Analysis of woody biomass utilization for heat, electricity, and CHP in a regional city of Japan. J Clean Prod 290:125665. https://doi.org/10.1016/j.jclepro.2020.125665
49. Gallagher M, Beard M, Clifford MJ, Watson MC (2016) An evaluation of a biomass stove safety protocol used for testing household cookstoves, in low and middle-income countries. Energy Sustain Dev 33:14–25. https://doi.org/10.1016/j.esd.2016.03.008
50. Gan Q, Xu J, Peng S, Yan F, Wang R, Cai G (2021) Effects of heating temperature on pore structure evolution of briquette coals. Fuel 296. https://doi.org/10.1016/j.fuel.2021.120651
51. Gendek A, Aniszewska M, Malaťák J, Velebil J (2018) Evaluation of selected physical and mechanical properties of briquettes produced from cones of three coniferous tree species. Biomass Bioenerg 117:173–179. https://doi.org/10.1016/j.biombioe.2018.07.025
52. Gimenes MH (2009) O uso turístico das comidas tradicionais: algumas reflexões a partir do Barreado, prato típico do litoral paranaense (Brasil). Turismo e Sociedade 2(1):8–24
53. Gioda A, Tonietto GB, de Leon AP (2019) Exposure to the use of firewood for cooking in Brazil and its relation with the health problems of the population. Ciencia e Saude Coletiva 24(8):3079–3088. https://doi.org/10.1590/1413-81232018248.23492017

54. Gold S, Seuring S (2011) Supply chain and logistics issues of bio-energy production. J Clean Prod 19(1):32–42. https://doi.org/10.1016/j.jclepro.2010.08.009
55. Gomez CC (2013) Biogas as an energy option: an overview. In: The Biogas Handbook. Elsevier, pp 1–16
56. Gould CF, Schlesinger SB, Molina E, Bejarano ML, Valarezo A, Jack DW (2020) Household fuel mixes in peri-urban and rural Ecuador: Explaining the context of LPG, patterns of continued firewood use, and the challenges of induction cooking. Energy Policy 136. https://doi.org/10.1016/j.enpol.2019.111053
57. Hazelton JA, Windhorst K, Amezaga JM (2013) Forest based biomass for energy in Uganda: stakeholder dynamics in feedstock production. Biomass Bioenerg 59:100–115. https://doi.org/10.1016/j.biombioe.2013.04.014
58. He L, English BC, Menard RJ, Lambert DM (2016) Regional woody biomass supply and economic impacts from harvesting in the southern U.S. Energy Economics 60:151–161. https://doi.org/10.1016/j.eneco.2016.09.007
59. Hoffmann BS, Szklo A, Schaeffer R (2012) An evaluation of the techno-economic potential of co-firing coal with woody biomass in thermal power plants in the south of Brazil. Biomass Bioenerg 45:295–302. https://doi.org/10.1016/j.biombioe.2012.06.016
60. Hollands AF, Daly H (2023) Modelling the integrated achievement of clean cooking access and climate mitigation goals: an energy systems optimization approach. Renew Sustain Energy Rev 173:113054. https://doi.org/10.1016/j.rser.2022.113054
61. Honkalaskar VH, Sohoni M, Bhandarkar UV (2014) Thermo-chemical modelling of a village cookstove for design improvement. Combust Theor Model 18(3):414–453. https://doi.org/10.1080/13647830.2014.921730
62. Instituto Brasileiro de Geografia e Estatística—IBGE (2021) Áreas Territoriais. https://www.ibge.gov.br/geociencias/organizacao-do-territorio/estrutura-territorial/15761-areas-dos-municipios.html?=&t=acesso-ao-produto. Accessed 18 Feb 2023
63. Intergovernmental Panel on Climate Change—IPCC (2022) Summary for policymakers. In: Pörtner HO, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, Alegría A, Craig M, Langsdorf S, Löschke S, Möller V, Okem A, Rama B (eds) Climate change 2022: impacts, adaptation, and vulnerability. Cambridge University Press, Cambridge and New York. https://doi.org/10.1017/9781009325844.001
64. International Energy Agency—IEA (2017) Energy access outlook 2017: from poverty to prosperity. World Energy Outlook Special Report
65. International Renewable Energy Agency—IRENA and International Energy Agency—IEA (2015) Biomass for heat and power. www.irena.org/Publications. Accessed 13 Jan 2023
66. Ishengoma EK, Igangula NH (2021) Determinants of household choice of cooking energy-mix in a peri-urban setting in Tanzania. Energy Sustain Dev 65:25–35. https://doi.org/10.1016/j.esd.2021.09.004
67. Jain T, Sheth PN (2019) Design of energy utilization test for a biomass cook stove: formulation of an optimum air flow recipe. Energy 166:1097–1105. https://doi.org/10.1016/j.energy.2018.10.180
68. Jelonek Z, Drobniak A, Mastalerz M, Jelonek I (2021) Emissions during grilling with wood pellets and chips. Atmos Environ X 12:100140. https://doi.org/10.1016/j.aeaoa.2021.100140
69. Joardder MUH, Islam MdK (2023) Thermophysical aspects of cooking processes. In: High-temperature processing of food products. Elsevier, pp 47–57
70. Jones D, Ryan CM, Fisher J (2016) Charcoal as a diversification strategy: the flexible role of charcoal production in the livelihoods of smallholders in central Mozambique. Energy Sustain Dev 32:14–21. https://doi.org/10.1016/j.esd.2016.02.009
71. Kaliyan N, Vance Morey R (2009) Factors affecting strength and durability of densified biomass products. Biomass Bioenerg 33(3):337–359. https://doi.org/10.1016/j.biombioe.2008.08.005
72. Kazungu I, Kumburu NP (2023) Agripreneurship as a panacea for food security in Tanzania: a systematic review. Heliyon 9

73. Kedir MF, Bekele T, Feleke S (2019) Problems of Mirt, and potentials of improved Gonzie and traditional open cook stoves in biomass consumption and end use emission in rural wooden houses of Southern Ethiopia. Sci Afr 3:64. https://doi.org/10.1016/j.sciaf.2019.e0
74. Kepple AW, Segall-Corrêa AM (2011) Conceituando e medindo segurança alimentar e nutricional Conceptualizing and measuring food and nutrition security. Cien Saude Colet 16(1):187–199. https://doi.org/10.1590/S1413-81232011000100022
75. Khanwilkar S, Gould CF, DeFries R, Habib B, Urpelainen J (2021) Firewood, forests, and fringe populations: Exploring the inequitable socioeconomic dimensions of liquefied petroleum gas (LPG) adoption in India. Energy Res Soc Sci 75:102012. https://doi.org/10.1016/j.erss.2021.102012
76. Kirchherr J, Reike D, Hekkert M (2017) Conceptualizing the circular economy: an analysis of 114 definitions. Resour Conserv Recycl 127:221–232. https://doi.org/10.1016/j.resconrec.2017.09.005
77. Kosemani BS, Ilori AT, Atere AO (2021) Modification and optimization of a baking oven for small scale bread production. Agric Sci 12(06):630–644. https://doi.org/10.4236/as.2021.126041
78. Kpalo SY, Zainuddin MF, Manaf LA, Roslan AM (2021) Evaluation of hybrid briquettes from corncob and oil palm trunk bark in a domestic cooking application for rural communities in Nigeria. J Clean Prod 284:124745. https://doi.org/10.1016/j.jclepro.2020.124745
79. Krecl P, Targino AC, Lara C, Oukawa GY, Soares J, Mollinedo EM (2023) Detecting local and regional air pollution from biomass burning at a suburban site. Atmos Environ 297. https://doi.org/10.1016/j.atmosenv.2023.119591
80. Kshirsagar MP, Kalamkar VR (2016) User-centric approach for the design and sizing of natural convection biomass cookstoves for lower emissions. Energy 115:1202–1215. https://doi.org/10.1016/j.energy.2016.09.048
81. Kuai B, Wang Z, Gao J, Tong J, Zhan T, Zhang Y, Lu J, Cai L (2022) Development of densified wood with high strength and excellent dimensional stability by impregnating delignified poplar by sodium silicate. Constr Build Mater 344. https://doi.org/10.1016/j.conbuildmat.2022.128282
82. Kumar N, Phillip E, Cooper H, Davis M, Langevin J, Clifford M, Stanistreet D (2021) Do improved biomass cookstove interventions improve indoor air quality and blood pressure? A systematic review and meta-analysis. Environ Pollut 290:117997. https://doi.org/10.1016/j.envpol.2021.117997
83. Kvestad I, Chandyo RK, Schwinger C, Ranjitkar S, Hysing M, Ulak M, Shrestha M, Shrestha L, Strand TA (2022) Biomass fuel use for cooking in Nepalese families and child cognitive abilities, results from a community-based study. Environ Res 212:113265. https://doi.org/10.1016/j.envres.2022.113265
84. Leme AS (2021) Josué de Castro and the metamorphoses of hunger in Brazil, 1932–1946. História, Ciências, Saúde - Manguinhos 28(4):1115–1135. https://doi.org/10.1590/S0104-59702021000400010
85. Li G, Hu R, Hao Y, Yang T, Li L, Luo Z, Xie L, Zhao N, Liu C, Sun C, Shen G (2023) CO_2 and air pollutant emissions from bio-coal briquettes. Environ Technol Innov 29. https://doi.org/10.1016/j.eti.2022.102975
86. Li X, Guo Y, Xiao J, Liu T, Zeng W, Hu J, He G, Rong Z, Zhu Z, Wu F, Ma W (2022) The effect of polluting cooking fuels on depression among older adults in six low- and middle-income countries. Sci Total Environ 838. https://doi.org/10.1016/j.scitotenv.2022.155690
87. Lima MDR, Massuque J, Bufalino L, Trugilho PF, Ramalho FMG, de Paula Protásio T, Hein PRG (2022) Clarifying the carbonization temperature effects on the production and apparent density of charcoal derived from Amazonia wood wastes. J Anal Appl Pyrol 166:105636. https://doi.org/10.1016/j.jaap.2022.105636
88. Lima MDR, Simetti R, de Assis MR, Trugilho PF, Carneiro ACO, Bufalino L, Hein PRG, de Paula Protásio T (2020) Charcoal of logging wastes from sustainable forest management for industrial and domestic uses in the Brazilian Amazonia. Biomass Bioenergy 142. https://doi.org/10.1016/j.biombioe.2020.105804

89. Lins LP, Martinez DG, Furtado AC, Padilha JC (2022) Biomethane generation and CO_2 recovery through biogas production using brewers' spent Grains. Biocatalysis Agric Biotechnol 102579. https://doi.org/10.1016/j.bcab.2022.102579
90. Liu Y, Li Z, Floess E, Zhang Y, Lam N, Mawusi SK, Shrestha P, Li X, Xue C, Liu G (2023) Field assessment of straw pellet combustion in improved heating stoves in rural Northeast China. J Environ Sci (China) 127:295–307. https://doi.org/10.1016/j.jes.2022.05.046
91. Lohani SP, Dhungana B, Horn H, Khatiwada D (2021) Small-scale biogas technology and clean cooking fuel: assessing the potential and links with SDGs in low-income countries—a case study of Nepal. Sustainable Energy Technol Assess 46:101301. https://doi.org/10.1016/j.seta.2021.101301
92. Lombradi GV, Parrini S, Atzori R, Stefani G, Romano D, Gastaldi M, Liu G (2021) Sustainable agriculture, food security and diet diversity. The case study of Tuscany, Italy. Ecol Model 458:109702. https://doi.org/10.1016/j.ecolmodel.2021.109702
93. Lubwama M, Yiga VA (2018) Characteristics of briquettes developed from rice and coffee husks for domestic cooking applications in Uganda. Renew Energy 118:43–55. https://doi.org/10.1016/j.renene.2017.11.003
94. Machado GO, Christoforo AL, Araujo VA, Lahr FAR (2016) Química da Madeira no Contexto Energético. EESC/USP, São Carlos
95. Maciel MDA, Troian A, Oliveira SV (2022) Brasil do agro, país da fome: pensando estratégias para o desenvolvimento sustentável. Espac Abierto 31(3):23–41
96. Mainimo EN, Okello DM, Mambo W, Mugonola B (2022) Drivers of household demand for cooking energy: a case of Central Uganda. Heliyon 8(3). https://doi.org/10.1016/j.heliyon.2022.e09118
97. Makonese T, Ifegbesan AP, Rampedi IT (2018) Household cooking fuel use patterns and determinants across southern Africa: evidence from the demographic and health survey data. Energy Environ 29(1):29–48. https://doi.org/10.1177/0958305X17739475
98. Mannucci P, Franchini M (2017) Health effects of ambient air pollution in developing countries. IJERPH 14(9):1048. https://doi.org/10.3390/ijerph14091048
99. Marques A, Rasinmäki J, Soares R, Amorim P (2018) Planning woody biomass supply in hot systems under variable chips energy content. Biomass Bioenerg 108:265–277. https://doi.org/10.1016/j.biombioe.2017.11.016
100. Martínez GJ (2015) Cultural patterns of firewood use as a tool for conservation: a study of multiple perceptions in a semiarid region of Cordoba, Central Argentina. J Arid Environ 121:84–99. https://doi.org/10.1016/j.jaridenv.2015.05.004
101. Mazzone A, Cruz T, Bezerra P (2021) Firewood in the forest: social practices, culture, and energy transitions in a remote village of the Brazilian Amazon. Energy Res Soc Sci 74. https://doi.org/10.1016/j.erss.2021.101980
102. Meira AM, Nolasco AM, Klingenberg D, de Souza EC, Dias Júnior AF (2021) Insights into the reuse of urban forestry wood waste for charcoal production. Clean Techn Environ Policy 23(10):2777–2787. https://doi.org/10.1007/s10098-021-02181-1
103. Mencarelli A, Cavalli R, Greco R (2022) Variability on the energy properties of charcoal and charcoal briquettes for barbecue. Heliyon 8(8). https://doi.org/10.1016/j.heliyon.2022.e10052
104. Menghini D, Marra FS, Allouis C, Beretta F (2008) Effect of excess air on the optimization of heating appliances for biomass combustion. Exp Thermal Fluid Sci 32(7):1371–1380. https://doi.org/10.1016/j.expthermflusci.2007.11.018
105. Monteiro H, Soares N (2022) Integrated life cycle assessment of a southern European house addressing different design, construction solutions, operational patterns, and heating systems. Energy Rep 8:526–532. https://doi.org/10.1016/j.egyr.2022.02.101
106. Muazu RI, Stegemann JA (2015) Effects of operating variables on durability of fuel briquettes from rice husks and corn cobs. Fuel Process Technol 133:137–145. https://doi.org/10.1016/j.fuproc.2015.01.022
107. Neufeld LM, Tolentino L (2012) Nutritional surveillance: developing countries. In: Encyclopedia of Human Nutrition. Elsevier Inc., pp 289–302

108. Niu X, Liu X, Zhang B, Zhang Q, Xu H, Zhang H, Sun J, Ho K-F, Chuang H-C, Shen Z, Cao J (2023) Health benefits from substituting raw biomass fuels for charcoal and briquette fuels: in vitro toxicity analysis. Sci Total Environ 866:161332. https://doi.org/10.1016/j.scitotenv.2022.161332
109. Okore MKL, Koske J, Letema S (2022) Household-based determinants of cooking and heating fuel mixes in informal settlements of Kisumu City, Kenya. Energy Sustain Dev 71:64–72. https://doi.org/10.1016/j.esd.2022.09.002
110. Olesen RS, Hall CM, Rasmussen LV (2022) Forests support people's food and nutrition security through multiple pathways in low- and middle-income countries. One Earth 5:1342–1353
111. Oliveira PRS, Trugilho PF, Oliveira TJP (2022) Briquettes of acai seeds: characterization of the biomass and influence of the parameters of production temperature and pressure in the physical-mechanical and energy quality. Environ Sci Pollut Res 29(6). https://doi.org/10.1007/s11356-021-15847-6
112. Pfau S, Hagens J, Dankbaar B, Smits A (2014) Visions of sustainability in bioeconomy research. Sustainability 6(3):1222–1249. https://doi.org/10.3390/su6031222
113. Pizarro-Loaiza CA, Antón A, Torrellas M, Torres-Lozada P, Palatsi J, Bonmatí A (2021) Environmental, social and health benefits of alternative renewable energy sources. Case study for household biogas digesters in rural areas. J Cleaner Prod 297:126722. https://doi.org/10.1016/j.jclepro.2021.126722
114. Prapas J, Baumgardner ME, Marchese AJ, Willson B, DeFoort M (2014) Influence of chimneys on combustion characteristics of buoyantly driven biomass stoves. Energy Sustain Dev 23:286–293. https://doi.org/10.1016/j.esd.2014.08.007
115. Protásio TP, Roque Lima MD, Scatolino MV, Silva AB, Rodrigues de Figueiredo IC, Gherardi Hein PR, Trugilho PF (2021) Charcoal productivity and quality parameters for reliable classification of Eucalyptus clones from Brazilian energy forests. Renew Energy 164:34–45. https://doi.org/10.1016/j.renene.2020.09.057
116. REN21 (2020) Renewables 2020 Global Status Report. REN21 Secretariat
117. Rose J, Bensch G, Munyehirwe A, Peters J (2022) The forgotten coal: charcoal demand in sub-Saharan Africa. World Dev Perspect 25. https://doi.org/10.1016/j.wdp.2022.100401
118. Rosenthal J, Quinn A, Grieshop AP, Pillarisetti A, Glass RI (2018) Clean cooking and the SDGs: integrated analytical approaches to guide energy interventions for health and environment goals. Energy Sustain Dev 42:152–159. https://doi.org/10.1016/j.esd.2017.11.003
119. Saleem M (2022) Possibility of utilizing agriculture biomass as a renewable and sustainable future energy source. Heliyon 8(2):e08905. https://doi.org/10.1016/j.heliyon.2022.e08905
120. Schettini BLS, Jacovine LAG, Torres CMME, Carneiro ACO, Villanova PH, Rocha SJSS, Rufino MPMX, Silva LB, Castro RVO (2022) Furnace-kiln system: how does the use of new technologies in charcoal production affect the carbon balance? Ind Crops Prod 187:115330. https://doi.org/10.1016/j.indcrop.2022.115330
121. Schueftan A, Sommerhoff J, González AD (2016) Firewood demand and energy policy in south-central Chile. Energy Sustain Dev 33:26–35. https://doi.org/10.1016/j.esd.2016.04.004
122. Seko T, Ishihara K, Suzuki T, Takagi S, Taga K, Iida Y, Shigematsu Y, Itabashi Y, Nakamichi Y, Fujiwara Y, Inada A, Yamashita Y (2022) Effects of moisture content of firewood used in the manufacture of Japanese traditional smoked-dried bonito, katsuobushi, on polycyclic aromatic hydrocarbon (PAH) generation. J Food Compos Anal 111. https://doi.org/10.1016/j.jfca.2022.104630
123. Setter C, Costa KLS, Oliveira TJP, Mendes RF (2020) The effects of kraft lignin on the physicomechanical quality of briquettes produced with sugarcane bagasse and on the characteristics of the bio-oil obtained via slow pyrolysis. Fuel Process Technol 210:106561. https://doi.org/10.1016/j.fuproc.2020.106561
124. Shrestha P, Zhang W, Mawusi SK, Li J, Xu J, Li C, Xue C, Liu G (2021) In-use emissions and usage trend of pellet heating stoves in rural Yangxin, Shandong Province. Environ Pollut 280. https://doi.org/10.1016/j.envpol.2021.116955

125. Silaen M, Taylor R, Bößner S, Anger-Kraavi A, Chewpreecha U, Badinotti A, Takama T (2020) Lessons from Bali for small-scale biogas development in Indonesia. Environ Innov Soc Trans 35:445–459. https://doi.org/10.1016/j.eist.2019.09.003
126. Simões GMF, Leder SM (2022) Energy poverty: the paradox between low income and increasing household energy consumption in Brazil. Energy Build 268. https://doi.org/10.1016/j.enbuild.2022.112234
127. Smith Kirk R, Woodward A Campbell-Lendrum D, Chadee D, Honda Y, Iu Q, Olwoch Jane M, Revich B, Sauerborn R (2014) Human health: impacts, adaptation, and co-benefits. In: FIeld Cb, Barros V, Dokken Dj, Mach Kj, Mastrandrea Md, Bilir Te, Chatterjee M, Ebi Kl, Estrada Yo, Genova Rc, Kissel Es, Maccracken S, White L. (org) Climate change 2014: impacts, adaptation, and vulnerability. Intergovernmental Panel on Climate Change, Cambridge. Cambridge University Press, Cambridge and New York
128. Sotannde OA, Oluyege AO, Abah GB (2010) Physical and combustion properties of charcoal briquettes from neem wood residues. Int Agrophys 24(2):189–194
129. Song C, He J, Zhang H (2021) Comprehensive zoning of biomass energy heating in EU countries reference for China from European experience. Chin J Popul Resour Environ 19(4):321–329. https://doi.org/10.1016/j.cjpre.2022.01.005
130. Srichat A, Vengsungnle P, Bootwong A (2017) A study to increasing the thermal efficiency of the improvements salt boiling stove which the fuel was firewood in Ban Dung area, Udon Thani province by CFD. In: Energy Procedia. Elsevier Ltd., pp 446–451
131. Stabridis O, van Gameren E (2018) Exposure to firewood: consequences for health and labor force participation in Mexico. World Dev 107:382–395. https://doi.org/10.1016/j.worlddev.2018.03.009
132. Thengane SK, Kung KS, Gomez-Barea A, Ghoniem AF (2022) Advances in biomass torrefaction: parameters, models, reactors, applications, deployment, and market. Prog Energy Combust Sci 93
133. Toka A, Iakovou E, Vlachos D, Tsolakis N, Grigoriadou AL (2014) Managing the diffusion of biomass in the residential energy sector: an illustrative real-world case study. Appl Energy 129:56–69. https://doi.org/10.1016/j.apenergy.2014.04.078
134. Tomazini CG, da Silva Leite CK (2016) Programa Fome Zero e o paradigma da segurança alimentar: Ascensão e queda de uma coalizão? Revista de Sociologia e Politica 24(58):13–30. https://doi.org/10.1590/1678-987316245801
135. Ullah S, Noor RS, Sanaullah GT (2021) Analysis of biofuel (briquette) production from forest biomass: a socioeconomic incentive towards deforestation. Biomass Conv Bioref. https://doi.org/10.1007/s13399-021-01311-5
136. United Nations Development Programme—UNDP and Oxford Poverty and Human Development Initiative—OPHI (2022). 2022 Global multidimensional poverty index (MPI): unpacking deprivation bundles to reduce multidimensional poverty. New York
137. Vasile M, Iordăchescu G (2022) Forest crisis narratives: illegal logging, datafication and the conservation frontier in the Romanian Carpathian Mountains. Polit Geogr 96. https://doi.org/10.1016/j.polgeo.2022.102600
138. Van Vliet EDS, Kinney PL, Owusu-Agyei S, Schluger NW, Ae-Ngibise KA, Whyatt RM, Jack DW, Agyei O, Chillrud SN, Boamah EA, Mujtaba M, Asante KP (2019) Current respiratory symptoms and risk factors in pregnant women cooking with biomass fuels in rural Ghana. Environ Int 124:533–540. https://doi.org/10.1016/j.envint.2019.01.046
139. Vasconcelos FAG (2005) Combate à fome no Brasil: uma análise histórica de Vargas a Lula Fighting hunger in Brazil: a historical analysis from Presidents Vargas to Lula. Revista de Nutrição 18(4):439–457. https://doi.org/10.1590/S1415-52732005000400001
140. Vásquez Lavin F, Barrientos M, Castillo Á, Herrera I, Ponce Oliva RD (2020) Firewood certification programs: key attributes and policy implications. Energy Policy 137. https://doi.org/10.1016/j.enpol.2019.111160
141. Vicente ED, Vicente A, Evtyugina M, Carvalho R, Tarelho LAC, Oduber FI, Alves C (2018) Particulate and gaseous emissions from charcoal combustion in barbecue grills. Fuel Process Technol 176:296–306. https://doi.org/10.1016/j.fuproc.2018.03.004

142. Vijay V, Kapoor R, Singh P, Hiloidhari M, Ghosh P (2022) Sustainable utilization of biomass resources for decentralized energy generation and climate change mitigation: a regional case study in India. Environ Res 212:113257. https://doi.org/10.1016/j.envres.2022.113257
143. Wander PR, Bianchi FM, Caetano NR, Klunk MA, Indrusiak MLS (2020) Cofiring low-rank coal and biomass in a bubbling fluidized bed with varying excess air ratio and fluidization velocity. Energy 203:117882. https://doi.org/10.1016/j.energy.2020.117882
144. Wang D, Liu L, Yuan Y, Yang H, Zhou Y, Duan R (2020) Design and key heating power parameters of a newly-developed household biomass briquette heating boiler. Renew Energy 147:1371–1379. https://doi.org/10.1016/j.renene.2019.09.081
145. Welfle DA, Chingaira S, Kassenov A (2020) Decarbonising Kenya's domestic and industry Sectors through bioenergy: an assessment of biomass resource potential and GHG performances. Biomass Bioenergy 142. https://doi.org/10.1016/j.biombioe.2020.105757
146. World Health Organization—WHO (2014) WHO guidelines for indoor air quality: household fuel combustion. World Health Organization, Geneva. https://apps.who.int/iris/handle/10665/141496. Accessed 9 Jan 2023
147. World Health Organization—WHO (2021a) Cooking fuels and technologies (database). https://www.who.int/publications/m/item/database-primary-reliance-on-fuels-and-technologies-for-cooking. Accessed 6 Feb 2023
148. World Health Organization—WHO (2021b) WHO global air quality guidelines. Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. World Health Organization, Geneva
149. World Health Organization (2022) WHO publishes new global data on the use of clean and polluting fuels for cooking by fuel type. https://www.who.int/news/item/20-01-2022-who-publishes-new-global-data-on-the-use-of-clean-and-polluting-fuels-for-cooking-by-fuel-type. Accessed 15 Feb 2023
150. World Health Organization—WHO (2023) Household air pollution data. https://www.who.int/data/gho/data/themes/air-pollution/household-air-pollution. Accessed 6 Feb 2023
151. Zhang Y, Zhi G, Jin W, Xu P, Li Z, Kong Y, Zhang H, Shen Y, Hu J (2023) Identifying the fundamental drives behind the 10-year evolution of northern China's rural household energy and emission: implications for 2030 and beyond. Sci Total Environ 865. https://doi.org/10.1016/j.scitotenv.2022.161053
152. Zhao J, Cao Y, Yu L, Liu X, Yang R, Gong P (2022) Future global conflict risk hotspots between biodiversity conservation and food security: 10 countries and 7 biodiversity hotspots. Glob Ecol Conserv 34. https://doi.org/10.1016/j.gecco.2022.e02036