International
Journal of Energy
Sector
Management

Biochar production from olive tree prunings by using open flame pyrolysis

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Received 31 October 2024
Revised 27 November 2024
Accepted 5 December 2024

Abstract

Purpose – The purpose of this study is to evaluate the potential of open-flame pyrolysis kilns as an efficient and sustainable solution for managing olive tree prunings in Mediterranean regions. By converting agricultural residues into biochar, this method aims to reduce biomass waste, mitigate CO_2 emissions, and enhance soil quality. The research seeks to highlight the environmental, economic and agricultural benefits of this approach, promoting its integration into local farming practices as part of a circular economy strategy and a broader effort toward climate change mitigation and sustainable development.

Design/methodology/approach – This study explores the use of open-flame pyrolysis kilns for converting olive tree prunings into biochar. Portable kilns were utilized to carbonize biomass residues in a controlled manner, offering an affordable and efficient solution with minimal technical requirements. The process was evaluated for carbon capture efficiency, biochar quality and emissions reduction. A life-cycle assessment was conducted to estimate potential environmental impacts, with a focus on CO_2 mitigation. Field trials assessed the feasibility of integrating this method into local agricultural practices, emphasizing its role in sustainable waste management, soil improvement and greenhouse gas emissions reduction.

Findings – This study demonstrates that open-flame pyrolysis kilns are an effective and low-cost method for converting olive tree prunings into high-quality biochar. The process achieved high carbon capture efficiency with minimal emissions, offering a sustainable alternative to traditional biomass disposal practices. Biochar produced improved soil properties, supporting nutrient retention and microbial activity. In addition, the method significantly reduced CO_2 emissions compared to burning prunings in fields. These findings highlight

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Funding: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Ethical approval: Not applicable as no animal or human subjects were involved.

Competing interests: There is no competing interest of personal or financial nature to disclose.

Authors' contributions: Conceptualization, E.T. and F.A.C.; methodology, A.M. and F.A.C.; software, S.T.; validation, V.G.P. and F.A.C.; formal analysis, A.M., E.T. and V.G.P.; investigation, A. M.; data curation, S.T.; writing – original draft preparation, E.T., V.G.P. and F.A.C.; writing – review and editing, E.T. and F.A.C.; visualization, E.T. and F.A.C.; supervision, V.G.P. and F.A.C.; project administration, E.T.. All authors have read and agreed to the published version of the manuscript.

Availability of data and materials: No datasets were generated or analysed during the current study.

International Journal of Energy
Sector Management

1750-6220
DOI 10.1108/IJESM-10-2024-0057

the environmental and agricultural benefits of biochar production, emphasizing its potential for waste management, climate change mitigation and enhancing soil health in Mediterranean farming systems.

Originality/value – This study introduces open-flame pyrolysis kilns as a novel, practical solution for managing olive tree prunings in Mediterranean regions, addressing both environmental and agricultural challenges. It highlights the dual benefits of reducing CO_2 emissions and producing biochar to enhance soil quality. The research provides an accessible, low-cost alternative for small-scale farmers, integrating sustainable waste management with climate change mitigation. By emphasizing the use of portable kilns and minimal technical requirements, this study offers valuable insights into promoting biochar production as part of circular economy practices, filling a critical gap in sustainable agriculture and renewable energy strategies.

Keywords Biochar, Material characterization, Open-flame pyrolysis, Pyrolisis

Paper type Research paper

1. Introduction

Olive tree prunings represent a significant source of agricultural biomass waste across Greece and other Mediterranean countries. Often disposed of through traditional open burning in fields, this practice not only destroys valuable biomass but also poses environmental hazards and contributes to the desertification of olive fields (Kougioumtzis *et al.*, 2019). Converting these prunings into biochar through pyrolysis presents a sustainable alternative.

Biochar, a porous material from biomass pyrolysis, acts as a carbon sink and can replace fossil carbon in industrial uses (European Biochar Foundation, 2020). Pyrolysis transforms biomass into stable carbonaceous products, presenting a pathway for carbon sequestration. Pyrogenic carbon capture and storage (PyCCS) leverages biochar to enhance soil quality and mitigate climate change through efficient carbon sequestration (Schmidt *et al.*, 2019b). This method is crucial for combating global warming, as it converts biomass into biochar that can sequester carbon in soil for centuries, enhancing crop yields and reducing greenhouse gas emissions (Gupta *et al.*, 2020). Despite its benefits, the widespread adoption of biochar remains limited.

Charcoal, produced via incomplete biomass combustion, has a history spanning 600 Myr and plays a crucial role in soil carbon content (Preston and Schmidt, 2006; Braadbaart *et al.*, 2009; Criscuoli *et al.*, 2014; Hart and Luckai, 2014). Forest fires naturally produce charcoal, typically accounting for 1%–10% of the burnt material, with regions like the Northwestern USA showing even higher percentages (Reisser *et al.*, 2016; DeLuca and Aplet, 2008). The positive impact of charcoal on forest soils and vegetation has been highlighted in various studies, including those in Sweden (Eriksson and Glav Lundin, 2021).

Open-flame pyrolysis, an ancient technique, has led to the creation of highly fertile soils known as Anthropogenic Dark Earths, or Terra Preta de Índio, in tropical rainforest ecosystems (Glaser and Birk, 2012). Modern adaptations, such as flame curtain pyrolysis kilns, are gaining popularity for their efficiency and cost-effectiveness in producing high-quality biochar from biomass residues, including olive prunings. Research indicates that optimizing kiln operation, such as adjusting feedstock layering rates, can significantly impact biochar yield and quality, achieving results comparable to continuous-scale pyrolysis units (Jayakumar *et al.*, 2023). Furthermore, the portability and ease of operation of these kilns make them suitable for diverse locations with abundant biomass.

Charcoal production has historically been integral to Greek culture, serving various purposes from cooking to industrial applications (Olson, 1991). However, traditional charcoal production faces challenges related to environmental conservation and sustainable forest management (Koulelis *et al.*, 2020). Recent findings at Alepotrypa Cave in southern Peloponnese highlight a transition toward more sustainable charcoal production methods, reflecting a broader commitment to environmental stewardship (Ntinou and Tsartsidou, 2017). This shift includes leveraging waste biomass or agricultural residues for charcoal production, promoting responsible consumption practices. The revelation of Terra Preta de Índio, also known as Black Earth or Melaina Gaia, has sparked a global surge in scientific inquiry, driving rapid advancements in research and study. These soils were consciously crafted by pre-Columbian and prehistoric communities of the Amazon over millennia (Sombroek *et al.*, 2002).

In Greece, annual agricultural waste production, predominantly from olive tree prunings, ranges from 1.4 to 3 million tons (Aravani *et al.*, 2022a). Composting these prunings can yield high-quality compost, offering potential for soil enrichment and sustainable agricultural practices (Charisiou *et al.*, 2016). However, traditional methods such as incineration of prunings exacerbate atmospheric pollution and climate change, highlighting the need for better management strategies (Charisiou *et al.*, 2015).

Recent studies underscore the potential of biochar in reforestation and soil improvement. For instance, biochar was assessed as a soil amendment in a study aimed at restoring degraded tropical lands. The native Tachigali vulgaris demonstrated superior survival, biomass production and canopy cover compared to exotic eucalyptus, indicating its potential for effective reforestation and soil improvement in degraded areas (De Farias *et al.*, 2016). Additionally, historic research, such as the analysis of former charcoal production sites in Cumbria, reveals the longstanding use of charcoal in various contexts, emphasizing its enduring significance (Hazell *et al.*, 2017).

This study aims to explore the potential of flame cup pyrolysis kilns for managing olive tree prunings and generating valuable byproducts, such as biochar. The research evaluates the feasibility and efficacy of this pyrolysis technique in converting agricultural biomass waste into biochar, thereby facilitating waste management initiatives and fostering sustainable agricultural practices. The study advocates for utilizing olive tree prunings directly in the field, promoting the concept of “bringing the factory to the field” to maximize resource utilization and minimize logistical overhead. More precisely, the innovation of this study lies in the application of open-flame pyrolysis on site with a low-cost decentralized scale, introducing therefore an innovative aspect for olive oil prunings management.

2. Theory

2.1 Pyrogenic carbon

Various solid materials, including charcoal, wood charcoal, wood char, biochar, biopanchar, biocarbon, activated carbon and biocharcoal, are categorized as forms of pyrogenic carbon. These materials are generated through the pyrolysis process of woody or other biomass, leading to a physicochemical transformation into charcoal. Pyrogenic carbon typically represents a stable form of aromatic carbon characterized by its distinctive architecture and properties. As an active and porous material, it boasts a significant internal surface area, reaching up to 1000 m^2/g, allowing for the retention and adsorption of numerous elements and compounds. Notably, pyrogenic carbon exhibits remarkable stability in natural environments. Biochar, in particular, demonstrates remarkable persistence in soil, undergoing minimal change over many centuries or even millennia. Its annual loss rate seldom exceeds 0.3%, underscoring its enduring presence and impact on soil ecosystems (Cotrufo *et al.*, 2016; Lehmann *et al.*, 2015; Zimmerman and Gao, 2013).

It is worth noticing that biochar is a product different from charcoal in terms of production processes, raw materials used, physicochemical properties and potential applications (Yadav and Sharma, 2024). These differences are summarized in the following Table 1:

The bulk of biochar produced globally finds its way into livestock diets before ultimately enriching the soil. Within the digestive systems of animals, biochar serves as a valuable addition, absorbing odors and nitrogenous compounds, thereby fostering optimal

Table 1. Biochar/charcoal differences

Aspect	Biochar	Charcoal
Applications	Serves various purposes: enhancing soil fertility and structure to rejuvenate depleted soil and enhance crop yield. Facilitating carbon sequestration by capturing atmospheric carbon dioxide and storing it in the soil, thereby increasing soil carbon content. Improving animal health by incorporating it into livestock feed. Decreasing the carbon footprint of construction materials like concrete and asphalt	Primarily used as a cooking and heating fuel. Its high combustion temperature (>1,100°C) is valuable for smelting metals. Activated charcoal is used for water filtration and medicinal applications
Production	Produced using modern pyrolysis methods at temperatures between 450 and 650°C. The process is quick (minutes to hours) and yields biochar and syngas. It is a negative emission technology, reducing greenhouse gases	Produced by older or modern pyrolysis methods at lower temperatures (~400°C), often lasting for days. This process releases gases and polycyclic aromatic hydrocarbons (PAHs), which can increase atmospheric CO_2 levels
Source materials	Derived from biomass or organic materials such as agricultural waste, plant residues and wood chips	Primarily from wood-based biomass, including: common charcoal: from wood, peat, coconut shell and petroleum. Lump charcoal: from hardwood. Sugar charcoal: from cane sugar. Barbecue charcoal briquettes: from sawdust and leftover wood
Physical and chemical properties	Greater porosity and surface area, enhancing soil structure and microbial habitat. Characteristics include: surface area: up to 1000 m^2/g; porosity: high; PAH content: generally low, with acceptable levels below 6 mg/kg according to EBC guidelines	Lower porosity due to production at lower temperatures. Decomposes faster in soil and serves as an insulator. Characteristics include surface area: generally lower, porosity: lower, PAH content: Can be higher, varying with production methods and sources

Source: Authors' own creation

gastrointestinal conditions and bolstering overall vitality (Schmidt *et al.*, 2019a). Recognized as a beneficial dietary supplement for birds and animals, it is now commonly included at a 1%–2% ratio in their feed. Acting as a "bioinducer" and "bioregulator", biochar plays a pivotal role in facilitating biochemical reactions within their digestive tracts. Its incorporation holds promise for enhancing disease resistance, promoting growth rates, improving the quality and quantity of animal products and even mitigating methane emissions. Moreover, biochar plays a multifaceted role in waste management within livestock operations, aiding in the management of both liquid and solid waste streams from stables. Its presence contributes to improved composting processes while simultaneously reducing greenhouse gas emissions. In agricultural contexts, biochar offers a myriad of benefits, including bolstering carbon storage, minimizing the need for inputs such as irrigation water, fertilizers and pesticides and enhancing overall productivity and food security (Ayaz *et al.*, 2021; Kabir *et al.*, 2023). Additionally, biochar's stable carbon storage, achieved by converting organic matter, aligns with agroecosystem mitigation strategies by reducing CO_2 emissions and enhancing soil carbon sequestration (Lehmann *et al.*, 2010).

2.2 *Biomass*

The term biomass encompasses biogenic residues originating from various sectors, including agriculture, livestock farming, fishing, food production industries, urban gardens, forests and municipal waste. Biomass plays a pivotal role in the transition toward a bioeconomy, aiming to gradually replace fossil fuels with renewable feedstock. This comprehensive societal shift encompasses a variety of sectors, actors and interests, facilitating far-reaching changes in today's production systems. The objectives pursued, such as reducing dependence on fossil fuels, mitigating climate change, ensuring global food security and increasing the industrial use of biogenic resources, are central to the bioeconomy concept (Priefer *et al.*, 2017). However, there is ongoing controversy over the pathways for achieving these objectives, highlighting the need for diverse approaches, research funding and stakeholder involvement in shaping the bioeconomy. Greece's extensive agricultural activities, which cover approximately 70% of the country's land area, highlight its high biomass potential (Papachristopoulos *et al.*, 2024). Representing an untapped resource, biomass holds significant potential for fostering circular economy principles, advancing sustainable development goals and reducing dependence on mineral-based materials. As a product of renewable sources, its judicious utilization can yield energy, biochar, soil amendments and a host of other valuable materials, all while substantially mitigating pollution levels. With its abundance, biomass stands poised to serve a multitude of purposes and recent research underscores its vast potential. For instance, studies indicate that the energy potential of agricultural biomass alone surpasses Greece's energy demands and rivals those of larger nations like China (Aravani *et al.*, 2022b).

2.3 *Pyrolysis of biomass*

Heating biomass within the temperature range of 350–900°C, with limited or no oxygen present, initiates the production of volatile gases known as pyrolytic gases, along with the formation of charcoal containing various inorganic elements. Upon cooling these gases to room temperature, they separate into two distinct fractions: the flammable, enduring pyrogenic gas (pyro-gas) and the non-flammable liquid, termed bio-oil. The proportion and quality of these three primary pyrolysis products are contingent upon the type of biomass utilized and the specific pyrolysis technique employed (Bridgwater and Peacocke, 2020).

Biochar, derived from agricultural waste, offers a cost-effective solution for environmental remediation, boasting unique physicochemical properties. Explores its production, applications and efficacy in removing pollutants, such as heavy metals and oil from contanated environments. Strategies to enhance biochar's effectiveness, including physical and chemical modifications, are discussed, highlighting its potential to mitigate water and soil contamination while promoting circular economy principles (Díaz *et al.*, 2024).

Moreover, bio-oil, a valuable byproduct, can also be obtained through this process. While the utilization of bio-oil for producing organic compounds dates back to the early 20th century with the practice of "wood distillation", which has since transitioned to the use of mineral raw materials, modern applications are evolving (Carazza *et al.*, 1994). Today, bio-oil demonstrates potential applications in diverse sectors such as the development of bioplastics, construction materials, agricultural and livestock farming and energy production.

A study on the steam pyrolysis of pinewood sawdust conducted in a conical spouted bed reactor provides detailed insights into the influence of temperature on product yields within the 500–800°C range. At 500°C, a high bio-oil yield of 75.4 Wt.% was obtained, indicating the reactor's suitability for this process. As the temperature increased, gas yields rose while liquid and char yields decreased. The study highlighted that steam was inert at lower temperatures (500°C–600°C) but influenced reactions at 700°C due to low gas residence time. At 800°C, gasification reactions predominated. The composition of the liquid fraction changed significantly with temperature, shifting from phenolic compounds at lower temperatures to hydrocarbons at higher temperatures. The char produced across the temperature range can be utilized as active carbon or an energy source (Fernandez *et al.*, 2022).

2.4 Open-flame pyrolysis

Open-flame pyrolysis represents an ancient technique for biochar production, originating from observations in forests (Artiola and Wardell, 2017). Researchers delving into the methods employed by Amazonian indigenous communities to pyrolyze vast amounts of biomass discovered their utilization of ground pits. This initially perplexing approach has been confirmed as a viable method for biomass pyrolysis (Schmidt and Taylor, 2014). Subsequent comprehension of the operational dynamics and relevant thermodynamics led to the development of open metal kilns-reactors, commonly referred to as flame cup pyrolysis kilns. As the name suggests, these kilns operate with flames covering the device, consuming incoming oxygen and preventing its penetration into lower layers where pyrolysis occurs. Upon completion, the fire is extinguished using water to facilitate controlled quenching. It is imperative to prevent residual fire from contacting atmospheric air. The process entails slow pyrolysis, maintaining temperatures around 500°C–600°C (Moser *et al.*, 2023). This method retains up to 50% of the total carbon in biomass, with the remainder consumed in combustion. While the process lacks full control and the produced biochar may not be perfectly homogeneous, numerous such devices, in various configurations, are operational worldwide (Cornelissen *et al.*, 2016).

The importance of biochar’s physicochemical properties in environmental applications underscores the need for careful consideration of production methods and post-pyrolysis modifications. Factors such as high porosity, specific surface area, nutrient content and functional groups are critical in enhancing biochar’s effectiveness as a soil conditioner and pollutant carrier (Gryta *et al.*, 2024). However, these benefits must be balanced against the environmental impact of the production process itself. Addressing the environmental concerns (Grigoroudis *et al.*, 2014) associated with open flame pyrolysis through improved practices and technologies can enhance the sustainability and overall effectiveness of biochar applications in agriculture and beyond (Petridis *et al.*, 2018a; Petridis *et al.*, 2018b). Traditional kiln technologies for charcoal production, including open-flame methods, are known for slow processes and significant emissions of gases like methane and carbon monoxide, along with aerosols that contribute to greenhouse gas emissions (Ioannou *et al.*, 2018; Kantartzis *et al.*, 2021). While retort kilns reduce emissions by recycling pyrolysis gases, they are costlier and require significant fuel for start-up.

3. Materials and methods

The open-flame pyrolysis experiment has been conducted approximately 15 times over the past two years in Argos, Greece. The experimental setup consists of a Kon-Tiki type kiln (Artiola and Wardell, 2017) capable of accommodating approximately 1,100 kg of raw materials, modified for easy transportation by a small truck with the assistance of two to four individuals (Plate 1). Specifically, a hand-driven gearbox has been integrated to facilitate the kiln’s emptying, adding approximately 30 kg to its weight. The kiln stands at a total height of approximately 130 cm, with an upper diameter of 150 cm. The entire construction is both simple and cost-effective, enabling widespread utilization of biomass pyrolysis without the need for specialized technical expertise or dedicated infrastructure. The process can be

Source: Authors own creation

Plate 1. The kiln

characterized as “slow pyrolysis”, occurring within a temperature range between 500°C and 650°C.

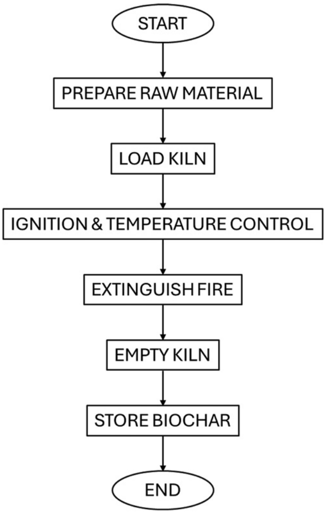
To provide a clear and structured overview of the experimental setup and process, a flowchart has been created. This flowchart outlines the key steps involved in preparing, setting up and conducting the open-flame pyrolysis experiment, as well as the post-pyrolysis procedures. It serves as a visual guide to ensure consistency and reproducibility of the experiment. The detailed flowchart can be found in Figure 1.

Pyrolysis is conducted outdoors usually during winter and spring at a non-windy or rainy day. Stringent adherence to fire safety regulations is paramount, with particular emphasis on preventing damage to the working personnel and to olive trees from close proximity or other fire accidents. The raw material utilized consists of green olive prunings, either fresh or dry, without any prior processing. The feedstock is layered within the kiln, with each new layer added immediately after the completion of pyrolysis for the previous layer. Plate 2 provides a visual representation of the typical experiment. Special attention is consistently directed toward maintaining a high intensity of flame, as a decrease in flame intensity leads to reduced biochar production and increased ash content. Finally, after 4–5 h, the fire is extinguished by introducing water into the kiln through an inlet located at the bottom. The resulting steam aids in activating the char by increasing the porous surface-to-volume ratio. Typical produced biochar is presented in Plate 3.

4. Results and discussion

A typical experiment using 1,150 kg of fresh olive prunings yielded 750 L of biochar after 4.5 h of pyrolysis (20% ash), weighing (laboratory dry) 140 kg of biochar. Olive oil prunings, meaning leaves and branches up to 3.5 cm in diameter, are the raw material that was pyrolyzed, where its characteristics are summarized in the following Table 2 (Aravani *et al.*, 2022b):

Typical samples of the produced biochar were sent outsourcing to Eurofins Umwelt Ost GmbH that is expert on analyses of physical and chemical processes for specific materials. The results are summarized in the following Table 3:



Source: Authors own creation

Figure 1. Experimental setup flowchart

Source: Authors own creation

Plate 2. Pyrolysis experiment

Also, the overall 16 EPA-PAH were found 6.7 mg/kg. This value is responsible for classifying the produced biochar as CLASS IV but further improvement of the *in situ* open-flame pyrolysis could update biochar classification. Furthermore, the specific surface area was found approximately 220 m^2 g^{-1} which can be considered successful for a typical absorbent, being however significantly lower than this of activated carbon (>700 m^2/g). Biochar samples were analyzed for microscopic characterization, again outsourced to James

Source: Authors own creation

Plate 3. Typical biochar produced

Table 2. Raw material physical and chemical properties

Total solids (%)	80
Volatile solids (%)	90
Biochemical methane potential (m^3/kg volatile solids)	0.20
CH_4 content (%)	55
C:N ratio	617
Moisture (Wt.%)	7.10
Ash (Wt.%)	4.75
C (%w/w)	48.59
H (%w/w)	6.21
O (%w/w)	43.40
N (%w/w)	0.70

Source: Authors' own creation

Table 3. Biochar properties

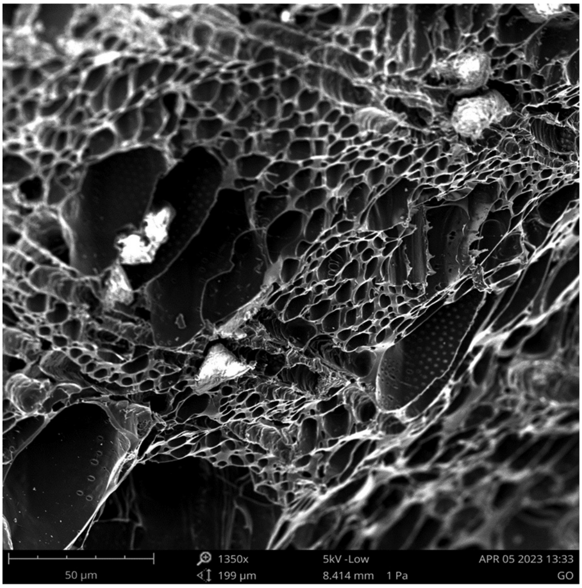
Parameter	Method	Unit	As received	Dry basis
Moisture	DIN 51718: 2002-06	% (w/w)	5.1	–
Ash content (550°C)	DIN 51719: 1997-07	% (w/w)	20.7	21.8
Carbon	DIN 51732: 2014-07	% (w/w)	73.2	77.1
Hydrogen	DIN 51732: 2014-07	% (w/w)	2.1	2.2
Total nitrogen	DIN 51732: 2014-07	g/kg	9.9	10.5
Sulphur (S), total	DIN 51724-3: 2012-07	% (w/w)	0.11	0.12
Oxygen	DIN 51733: 2016-04	% (w/w)	4.7	5.0

Source: Authors' own creation

Madison University, USA. A typical picture of the micro-structure is depicted in Figure 2. Also, the pores distribution resulted that the material is mainly characterized by micro-pores.

Finally, experiments carried out to identify the chemical composition of the water used for fire extinguishing. The results are summarized in Table 4.

The water was found quite alkaline, with high conductivity. Although of high sodium concentrations, it was also found rich in K, being therefore useful for irrigation after the appropriate processing to lower the pH and the Na concentration. In this context, the most straightforward and least burdensome proposal appears to be layering the powdered biochar together with other sorbent materials in stalls. Here, they will be "impregnated" with urea



Source: Authors own creation

Figure 2. Microstructure of the produced biochar

Table 4. Water chemical composition

pH	12.31
Conductance (mS/cm)	6.73
Ca (ppm)	6.4
Mn (ppm)	0.12
Fe (ppm)	0.4
K (ppm)	1253
N (ppm)	291
Cu (ppm)	0.03
Zn (ppm)	2.3

Source: Authors' own creation

and other components from the animal manures. This approach allows for the removal of manure while simultaneously preparing high-quality compost.

Overall, the procedure demonstrates that approximately one-third of the total carbon content in the initial biomass (raw material) was captured through carbon capture. Industrial-grade pyrolysis machines boast significantly higher carbon retention rates, often achieving up to 70%. Moreover, they possess the capability to harness the energy inherent in the biomass, a resource typically lost as thermal energy in open-flame pyrolysis, underscoring their efficiency. The decision whether to adopt this method should be based on a comprehensive evaluation of both its total cost and environmental impact, including factors such as the establishment of industrial units and the logistics of collecting and transporting residual biomass. Furthermore, the availability of certain types of residual biomass may be limited to specific seasons, posing challenges to continuous operation. Comparatively, open-flame pyrolysis of field prunings should be juxtaposed with conventional burning rather than industrial pyrolysis or other residual biomass management techniques. Notably, no other known method currently rivals its potential for widespread and immediate application in addressing the pressing need for carbon sequestration and storage.

5. Conclusions

This study demonstrates the practicality and environmental benefits of open-flame pyrolysis kilns for converting residual biomass, such as olive tree prunings, into high-quality biochar directly in agricultural fields. The Kon-Tiki kiln method provides a low-cost, scalable, and decentralized solution for biomass management, effectively mitigating CO_2 emissions while promoting sustainable agriculture.

The produced biochar exhibits desirable properties for soil enhancement, such as improved porosity and nutrient retention, making it suitable for diverse agricultural applications. Additionally, the reduction of harmful emissions associated with traditional burning methods underscores the environmental significance of adopting this approach.

By bridging the gap between traditional practices and modern sustainable solutions, this method aligns with global climate mitigation goals and circular economy principles. Future research should focus on optimizing kiln design, improving biochar quality, and evaluating its long-term impacts on soil health and carbon sequestration. Widespread adoption of open-flame pyrolysis offers a promising pathway for addressing the dual challenges of waste management and climate change, fostering resilience and sustainability in agricultural systems.

References

Aravani, V., Tsigkou, K., Papadakis, V.G. and Kornaros, M. (2022a), "Biochemical methane potential of most promising agricultural residues in Northern and Southern Greece", *Chemosphere*, Vol. 296, p. 133985.

Aravani, V.P., Sun, H., Yang, Z., Liu, G., Wang, W., Anagnostopoulos, G., Syriopoulos, G., Charisiou, N.D., Goula, M.A., Kornaros, M. and Papadakis, V.G. (2022b), "Agricultural and livestock sector's residues in Greece and China: comparative qualitative and quantitative characterization for assessing their potential for biogas production", *Renewable and Sustainable Energy Reviews*, Vol. 154, p. 111821, doi: 10.1016/j.rser.2021.111821.

Artiola, J.F. and Wardell, L. (2017), *Guide to Making and Using Biochar for Gardens in Southern AZ*, The University of AZ, College of Agriculture and Life Sciences, Tuscon, AZ, p. AZ1752.

Ayaz, M., Feiziene, D., Tilvikiene, V., Akhtar, K., Stulpinaite, U. and Ikbal, R. (2021), "Biochar role in the sustainability of agriculture and environment", *Sustainability*, Vol. 13 No. 3, p. 1330, doi: 10.3390/su13031330.

Braadbaart, F., Poole, I. and van Brussel, A.A. (2009), “Preservation potential of charcoal in alkaline environments: an experimental approach and implications for the archaeological record”, *Journal of Archaeological Science*, Vol. 36 No. 8, pp. 1672-1679, doi: 10.1016/j.jas.2009.03.006.

Bridgwater, A.V. and Peacocke, G.V.C. (2020), “Fast pyrolysis processes for biomass”, *Renewable and Sustainable Energy Reviews*, Vol. 4 No. 1, pp. 1-73.

Carazza, F., Rezende, M.E.A., Pasa, V.M.D. and Lessa, A. (1994), “Fractionation of wood tar”, *Proc. Adv. Thermochem. Biomass Convers*, Vol. 2, p. 1465.

Charisiou, N.D., Konstantakou, P.P. and Papadakis, V.G. (2016), “Exploitation of olive tree prunings as raw material for the production of high quality compost”, *Environmental Engineering and Management Journal*, Vol. 15 No. 12, pp. 2709-2717.

Charisiou, N.D., Paraskeva, C., Goula, M.A. and Papadakis, V.G. (2015), “Techo-economical and sustainability analyses for multilateral exploitation of olive tree cultivation residues”, *Journal of Environmental Science and Technology Research (JESTR)*, Vol. 1 No. 1, pp. 1-6.

Cornelissen, G., Pandit, N.R., Taylor, P., Pandit, B.H., Sparrevik, M. and Schmidt, H.P. (2016), “Emissions and char quality of flame-curtain ‘kon tiki’ kilns for farmer-scale charcoal/biochar production”, *Plos One*, Vol. 11 No. 5, p. e0154617, doi: 10.1371/journal.pone.0154617.

Cotrufo, M.F., Boot, C., Abiven, S., Foster, E.J., Haddix, M., Reisser, M., Wurster, C.M., Bird, M.I. and Schmidt, M.W.I. (2016), “Quantification of pyrogenic carbon in the environment: an integration of analytical approaches”, *Organic Geochemistry*, Vol. 100, pp. 42-50, doi: 10.1016/j.orggeochem.2016.07.007.

Criscuoli, I., Alberti, G., Baronti, S., Favilli, F., Martinez, C., Calzolari, C., Pusceddu, E., Rumpel, C., Viola, R. and Miglietta, F. (2014), “Carbon sequestration and fertility after centennial time scale incorporation of charcoal into soil”, *PLoS ONE*, Vol. 9 No. 3, p. e91114, doi: 10.1371/journal.pone.0091114.

De Farias, J., Marimon, B.S.D., Carvalho, L., Silva, R., Petter, F.A.R., Andrade, Morandi, P.S. and Marimon-Junior, B.H. (2016), “Survival and growth of native *Tachigali vulgaris* and exotic *Eucalyptus urophylla* × *Eucalyptus grandis* trees in degraded soils with biochar amendment in southern Amazonia”, *Forest Ecology and Management*, Vol. 368, pp. 173-182, doi: 10.1016/j.foreco.2016.03.022.,

DeLuca, T.H. and Aplet, G.H. (2008), “Charcoal and carbon storage in forest soils of the Rocky Mountain west”, *Frontiers in Ecology and the Environment*, Vol. 6 No. 1, pp. 18-24, doi: 10.1890/070070.

Díaz, B., Sommer-Márquez, A., Ordoñez, P.E., Bastardo-González, E., Ricaurte, M. and Navas-Cárdenas, C. (2024), “Synthesis methods, properties and modifications of biochar-based materials for wastewater treatment: a review”, *Resources*, Vol. 13 No. 1, p. 8, doi: 10.3390/resources13010008.

Eriksson, O. and Glav Lundin, L. (2021), “Legacies of historic charcoal production affect the forest flora in a Swedish mining district”, *Nordic Journal of Botany*, Vol. 39 No. 11, p. e03312, doi: 10.1111/njb.03312.

European Biochar Foundation (2020), “Guidelines for a sustainable production of biochar, eur. Biochar found”, Version 9, pp. 1-22, available at: www.european-biochar.org/biochar/media/doc/ebc-guidelines.pdf

Fernandez, E., Santamaria, L., Amutio, M., Artetxe, M., Arregi, A., Lopez, G., Bilbao, J. and Olazar, M. (2022), “Role of temperature in the biomass steam pyrolysis in a conical spouted bed reactor”, *Energy*, Vol. 238 No. c, p. 122053, doi: 10.1016/j.energy.2021.122053.

Glaser, B. and Birk, J.J. (2012), “State of the scientific knowledge on properties and genesis of anthropogenic dark earths in Central Amazonia (terra preta de índio)”, *Geochimica et Cosmochimica Acta*, Vol. 82, pp. 39-51.

Grigoroudis, E., Petridis, K. and Arabatzis, G. (2014), “RDEA: a recursive DEA based algorithm for the optimal design of biomass supply chain networks”, *Renewable Energy*, Vol. 71, pp. 113-122, doi: 10.1016/j.renene.2014.05.001.

Gryta, A., Skic, K., Adamczuk, A., Skic, A., Marciniak, M., Jozefaciuk, G. and Boguta, P. (2024), “The importance of the targeted design of biochar physicochemical properties in microbial inoculation for improved agricultural productivity–a review”, *Agriculture*, Vol. 14 No. 1, p. 37, doi: 10.3390/agriculture14010037.

Gupta, K.D., Gupta, K.C., Dubey, R., Fagodiya, R.K., Sharma, G., Keertika, A., Noor Mohamed, M.B., Dev, R. and Shukla, A.K. (2020), “Role of biochar in carbon sequestration and greenhouse gas mitigation”, in Singh, J. and Singh, C. (Eds), *Biochar Applications in Agriculture and Environment Management*, Springer, Cham, doi: 10.1007/978-3-030-40997-5_7.

Hart, S.A. and Luckai, N.J. (2014), “Charcoal carbon pool in North American boreal forests”, *Ecosphere*, Vol. 5 No. 8, p. 99.

Hazell, Z., Crosby, V., Oakey, M. and Marshall, P. (2017), “Archaeological investigation and charcoal analysis of charcoal burning platforms, Barbon, Cumbria, UK”, *Quaternary International*, Vol. 458, pp. 178-199, doi: 10.1016/j.quaint.2017.05.025.

Ioannou, K., Tsantopoulos, G., Arabatzis, G., Andreopoulou, Z. and Zafeiriou, E. (2018), “A spatial decision support system framework for the evaluation of biomass energy production locations: case study in regional unit of drama, Greece”, *Sustainability*, Vol. 10 No. 2, p. 531, doi: 10.3390/su10020531.

Jayakumar, A., Morrisset, D., Koutsomarkos, V., Wurzer, C., Hadden, R.M., Lawton, L., Edwards, C. and Masek, O. (2023), “Systematic evaluation of pyrolysis processes and biochar quality in the operation of low-cost flame curtain pyrolysis kiln for sustainable biochar production”, *Current Research in Environmental Sustainability*, Vol. 5, p. 100213, doi: 10.1016/j.crsust.2023.100213.

Kabir, E., Kim, K.H. and Kwon, E.E. (2023), “Biochar as a tool for the improvement of soil and the environment”, *Frontiers in Environmental Science*, Vol. 11, doi: 10.3389/fenvs.2023.1324533.

Kantartzis, A., Daoutis, C., Eftaxias, A., Arabatzis, G. and Diamantis, V. (2021), “Biomass residues adjacent forest roads in two different forest species (*Fagus sylvativa* and *Pinus brutia*): quantities and evaluation of their biogas production potential”, *IOP Conference Series: Earth and Environmental Science*, Vol. 899 No. 1, p. 12030, doi: 10.1088/1755-1315/899/1/012030.

Kougioumtzis, M.A., Karampinis, E., Grammelis, P. and Kakaras, E. (2019), “Exploitation of olive tree prunings, evaluation of an integrated harvesting demonstration in Central Greece”, *27th European Biomass Conference and Exhibition*, pp. 312-317, doi: 10.5071/27thEUBCE2019-1DV.3.17

Koulelis, P., Solomou, A. and Fassouli, V. (2020), “Sustainability constraints in Greece. Focusing on forest management and biodiversity”, *Proceedings of the 9th International Conference on Information and Communication Technologies in Agriculture, Food and Environment (HAICTA 2020), Thessaloniki, Greece*

Lehmann, J., Amonette, J.E. and Roberts, K.G. (2010), “Role of biochar in mitigation of climate change”, in Hillel, D. and Rosenzweig, C. (Eds), *Handbook of Climate Change and Agroecosystems, Impacts, Adaptation and Mitigation*, Columbia University, USA and Goddard Institute for Space Studies, USA, ICP Series on Climate Change Impacts, Adaptation and Mitigation, Vol. 1, doi: 10.1142/p755.

Lehmann, J., Abiven, S., Kleber, M., Pan, G., Singh, B.P., Sohi, S.P. and Zimmerman, A.R. (2015), “Persistence of biochar in soil”, in Lehmann, J. and Joseph, S.D. (Eds), *Biochar for Environmental Management*, Routledge ed, New York, NY, pp. 235-282.

Moser, K., Wopienka, E., Pfeifer, C., Schwarz, M., Sedlmayer, I. and Haslinger, W. (2023), “Screw reactors and rotary kilns in biochar production – a comparative review”, *Journal of Analytical and Applied Pyrolysis*, Vol. 174, p. 106112, doi: 10.1016/j.jaap.2023.106112.

Ntinou, M. and Tsartsidou, G. (2017), “Domestic and ritual use of plants and fuels in the neolithic cave of alepotrypa, Southern Peloponnese, Greece: the wood charcoal and phytolith evidence”, *Quaternary International*, Vol. 457, pp. 211-227, doi: 10.1016/j.quaint.2016.11.028.

Olson, S.D. (1991), “Firewood and charcoal in classical Athens”, *The Journal of the American School of Classical Studies in Athens*, Vol. 60 No. 3, pp. 411-420.

Papachristopoulos, E., Tsiaras, E., Papadakis, V.G. and Coutelieris, F.A. (2024), “Design of a biogas power plant that uses olive tree pruning and olive kernels in Achaia, Western Greece”, *Sustainability*, Vol. 16 No. 1, p. 187, doi: 10.3390/su16010187.

Petridis, K., Grigoroudis, E. and Arabatzis, G. (2018a), “A conceptual model for biomass supply chain sustainability”, *International Journal of Social Ecology and Sustainable Development*, Vol. 9 No. 2, pp. 37-53, doi: 10.4018/IJSESD.2018040104.

Petridis, K., Grigoroudis, E. and Arabatzis, G. (2018b), “A goal programming model for a sustainable biomass supply chain network”, *International Journal of Energy Sector Management*, Vol. 12 No. 1, pp. 79-102, doi: 10.1108/IJESM-09-2017-0002.

Preston, C.M. and Schmidt, M.W.I. (2006), “Black (pyrogenic) carbon: a synthesis of current knowledge and uncertainties with special consideration of Boreal regions”, *Biogeosciences*, Vol. 3 No. 4, pp. 397-420.

Priefer, C., Jörissen, J. and Frör, O. (2017), “Pathways to shape the bioeconomy”, *Resources*, Vol. 6 No. 1, p. 10, doi: 10.3390/resources6010010.

Reisser, M., Purves, R.S., Schmidt, M.W.I. and Abiven, S. (2016), “Pyrogenic carbon in soils: a literature-based inventory and a global estimation of its content in soil organic carbon and stocks”, *Frontiers in Earth Science*, Vol. 4, p. 80, doi: 10.3389/feart.2016.00080.

Schmidt, H.P. and Taylor, P. (2014), “Kon-Tiki flame cap pyrolysis for the democratization of biochar production”, *The Biochar-Journal*, pp. 14-24, available at: www.biochar-journal.org/en/ct/3

Schmidt, H.P., Hagemann, N., Draper, K. and Kammann, C. (2019a), “The use of biochar in animal feeding”, *PeerJ*, Vol. 7, p. e7373.

Schmidt, H.P., Anca-Couce, A., Hagemann, N., Werner, C., Gerten, D., Lucht, W. and Kamman, C. (2019b), “Pyrogenic carboncarture and storage”, *GCB Bioenergy*, Vol. 11 No. 4, pp. 573-591, doi: 10.1111/gcbb.12553.

Sombroek, W., Kern, D., Rodrigues, T., Cravo, M.S., Jarbas, T.C., Woods, W. and Glaser, B. (2002), “Terra preta and terra Mulata: pre–Columbian amazon kitchen Middens and agricultural fields, their sustainability and their replication”, 17th WCS, *Thailand*, Symposium, No. 18.

Yadav, K. and Sharma, R.L. (2024), “Comparative study of biochar and charcoal and their application in the construction industry”, *Asian Journal of Civil Engineering*, Vol. 25 No. 2, pp. 1-16, doi: 10.1007/s42107-023-00835-7.

Zimmerman, A.R. and Gao, B. (2013), “The stability of biochar in the environment”, in Ladygina, N. and Rineau, F. (Eds), *Biochar and Soil Biota*, CRC press, Boca Raton, FL, pp. 1-40.

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