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REVIEW

Sustainable Biochar Production from Date Palms: A Scoping Review of Solutions for Arab Regions

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Abstract

H. A. Burezq. 2024. Sustainable Biochar Production from Date Palms: A Scoping Review of Solutions for Arab Regions. Int. J. Agric. Nat. Resour. 157-175. This scoping review investigates the potential of date palm biochar for sustainable agriculture in Arab nations. Analysis reveals that the 82.35 million date palm trees across 18 Arab countries could yield 576,423 tons of biochar annually, offering a significant resource for improving soil sustainability. This study systematically examines existing literature on date palm biochar production, its impact on soil health (including water and nutrient conservation), optimal application methods, and its potential to enhance food security in arid regions. The findings highlight the economic and environmental benefits of biochar, particularly for small-scale farmers, and discuss the Kuwait Biochar Initiative as a successful model for wider adoption of this sustainable agricultural practice. The review concludes by emphasizing the global potential of date palm biochar for sustainable agriculture and soil health.

Keywords: Biochar, date palm, food security, organic amendments, pyrolysis, sandy soils, scoping review, soil sustainability, sustainable agriculture.

Highlights

- This review analyzes date palm biochar's potential, highlighting opportunities and challenges for widespread implementation.
- Arab region's vast date palm resource offers significant biochar production potential for sustainable agriculture.
- Date palm biochar: A sustainable soil amendment enhancing water retention and nutrient use in arid farming.
- Improved crop yields and soil health are demonstrated through date palm biochar application in field trials.
- The Kuwait Biochar Initiative showcases a successful model for biochar adoption in arid and developing regions.

Introduction

Date palm cultivation occurs in eighteen of the twenty-three Arab countries, where 82.35 million productive trees flourish across 880,760 hectares out of the total of 70.18 million hectares of culti-

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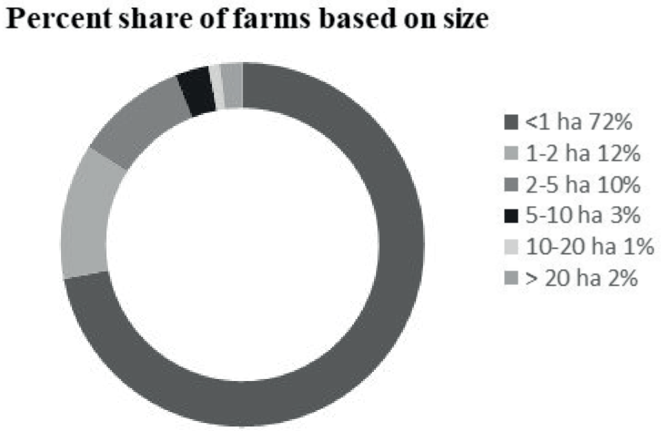

Figure 1. Share of various-sized farms in 111 countries (FAO,2014)

vated land (AOAD, 2008). Globally, agricultural land is primarily divided among small, medium, and large farms. There are over 570 million farms worldwide, with 90% operated by individuals or families. These family-run farms occupy 70-80% of global farmland land and contribute approximately 80% of global food production (FAO, 2014).

Notably, about 84% of these farms cover less than 2 hectares each, collectively managing 12% of global agricultural land (Lowder et al., 2016). Among them, farms smaller than one Ha account for 72%, yet they control only 8% of the agricultural land. Farms between 1 and 2 Ha make up 12% of the total and hold 4% of the land. Those ranging from 2 to 5 Ha are 10% of all farms and manage 7% of the land (Figure 1). In sharp contrast, just 1% of farms worldwide exceed 50 hectares, but this small group controls a significant 65% of agricultural land in the world (FAO, 2014).

However, the productivity of these small-scale farms remains limited and must be enhanced to support a global population projected to exceed 9 billion by 2050. Achieving this requires prioritizing investments in soil health as a critical component of national development strategies. The United Nations Food and Agriculture Organization highlights that sustainable soil management could lead to a significant 58% increase in food production.

An analysis of the total Kuwaiti farm count (8,033) reveals a distribution comprising poultry operations (0.47%), cattle husbandry (0.52%), crop and vegetable cultivation (48.7%), and sheep and goat farming (50.3%) (Al-Naser et al., 2020). Notably, the majority of farms involved in crop and vegetable cultivation are smaller in size, occupying less than 2 Ha. There was a 5.8% increase in the total number of farms from 2013 (7,590) to 2017 (8,033). A similar trend is observed across other GCC countries, where smaller farms are often established on sandy soils. These sandy soils, characterized by low organic carbon and clay content, are naturally considered infertile and require special attention to improve soil health (Akça & Atatanır, 2020; Shahid et al., 2004). The ongoing need to boost soil health, primarily through improving soil structure and optimizing nutrient levels, highlights the importance of integrated soil fertility management (ISFM) as a key strategy for sustainable agriculture. Enhancing soil nutrient reservoirs, recycling nutrients on farms, reducing nutrient losses, and improving the efficiency of input applications are particularly crucial on soils with inherent limitations, even more so than on fertile soils. Using organic amendments not only improves the physical properties of soil but also enhances the effectiveness of inorganic fertilizers, creating beneficial interactions within the biological and chemical systems of the soil. Efforts have been made to double crop yields by combining organic and inorganic soil amendments in sandy soils, along with significant water conservation (Burezq, 2019; Abdelhak, 2022; Yaqoobi et al., 2022). However, many organic amendments have a short lifespan in the soil, requiring frequent replenishment. This need for ongoing application can place a financial burden on farmers and increase production costs. Given these challenges, attention has shifted towards incorporating biochar as a soil amendment to support plant growth (Kammann et al., 2015; Yang et al., 2022). This approach has the potential to reduce fertilizer use by up to 30% while also enhancing soil carbon sequestration and fertility (Vaughn et al., 2015). Biochar is also recognized for increasing cation exchange capacity and improving nutrient retention (Lyu et al., 2022). Its positive impact extends to soil chemistry, physical properties (Lyu et al., 2022), reducing greenhouse gas emissions (Shakoor et al., 2021), and mitigating wind erosion (Burezq, 2019). Beyond improving soil health, biochar has gained attention as a sustainable method for environmentally friendly agricultural residue management as well. However, opinions within the global scientific community regarding biochar are divided. While many experts emphasize its beneficial effects on soil and plant growth, there are also dissenting views (Elbasiouny & Elbehiry, 2023) highlighting potential drawbacks. Although a vast amount of literature praises the positive effects of biochar, fewer studies address its limitations. Building on the work of Lyu et al. (2013), our team has taken on the challenge of exploring the broader potential of biochar in improving soil health.

Recycling Agricultural Residues into Biochar.

Biochar was produced using date palm fronds through a biochar production system as detailed by (Meng et al., 2022). The conversion of animal manure into biochar is achieved via high-temperature pyrolysis (>500 °C) in an oxygen-free environment. Incorporating such biochar into soil is an effective strategy for boosting nutrient retention.

Biochar Properties, Composition, and Pyrolysis Temperature

The properties of biochar are mainly determined by the temperature and processing conditions employed during its production from specific feedstock's (Burezq & Davidson., 2023). Biochar thus needs to be carefully chosen with the intended application in mind (Burezq & Davidson, 2023). Biochar exhibits elevated carbon content, hosts various functional groups (Shakoor et al., 2021), and boasts a substantial surface area (25 m^2 per gram). To a certain extent, it contains substances akin to humic and fluvic compounds (Liu et al. 2020), alongside a notable degree of stability against chemical and microbial degradation (Liu et al., 2020).

Subjecting the feedstock to heat without the presence of air, a process known as pyrolysis, results in the generation of energy-rich volatiles and gases. Throughout this process, hydrogen and oxygen are preferentially removed, leading to the formation of a stable and biologically recalcitrant carbon-rich substance known as biochar (Lehmann et al., 2021). The composition of biochar is significantly influenced by factors such as pyrolysis temperature, residence time, and the type of feedstock (Joseph et al., 2010; Tomczyk et al., 2020; Burezq & Davidson, 2023). As such, there is no fixed composition for biochar, and the conversion of biomass into biochar hinges on the specific characteristics of the feedstock (Shakoor et al., 2021). Biochar is typically produced through pyrolysis within the temperature range of 350-1,000 °C and under hypoxic or anoxic conditions, using a diverse array of feedstocks (Meyer et al., 2017). This thermochemical conversion process yields a stable carbon product with minimal to no ash (Chen et al., 2021; Werner et al., 2018), capable of persisting in the soil for decades (Singh et al., 2012; Zhang et al., 2019).

Research indicates that elevating the pyrolysis temperature significantly impacts carbon content, which rises proportionally with temperatures ranging from 300 to 800 °C. Conversely, elements like hydrogen and nitrogen experience a reduction.

Lower pyrolysis temperatures enhance the availability of nitrogen and phosphorous, while higher temperatures elevate the availability of potassium from the biochar. Due to the diverse nature of feedstocks, the nutrient content of biochar is not standardized; however, common elements include carbon, nitrogen, and hydrogen, as well as other elements like sodium, calcium, magnesium, and potassium (Zhang et al., 2015). Biochar shows promise in terms of its potential to provide plants with phosphorous and potassium as well (Lyu et al., 2022; Song et al., 2020; Masto et al., 2013). Nonetheless, the presence of macronutrients such as nitrogen, phosphorous, and potassium in biochar does not necessarily reflect their immediate availability to plants (Spokas et al., 2012). These nutrients are intricately bound within the stable carbon structure and functional groups of biochar.

Biochar derived from sawdust exhibits notable attributes, boasting the highest surface area, minimal ash content, elevated aromaticity, and carbon content (Srinivasan et al., 2015). In a general context, various types of biochar show low concentrations of heavy metals such as chromium, copper, zinc, arsenic, cadmium, mercury, and lead. Per the regulations stipulated by the USEPA (40 CFR Part 503), these biochar varieties are deemed suitable for land application (Srinivasan et al., 2015). Biochar generation is viable from Acacia saligna at 380 °C, while sawdust can be converted into biochar at 450 °C, each containing approximately 17.7% and 16.2% of humic and fulvic materials, respectively (Liu et al., 2020). The pH level of the soil plays a pivotal role in governing the availability of these materials from biochar (Chen et al., 2021). Song et al. (2020) investigated nutrient release from biochar obtained from Arundo donax (giant reed) within the temperature range of 300-600 °C. Their findings revealed a slow release of water-soluble NH_4 after 120 hours, whereas water-soluble PO_4^{3-} and K^+ exhibited rapid release within 24 hours. Interestingly, the introduction of biochar to forest soils spurred nitrification due to the sorption of phenolics, which function as nitrification inhibitors (Oh & Kim, 2022; Makoto & Koike, 2021). Consequently, when sourcing biochar from commercial suppliers, the total content of nitrogen, phosphorous, and potassium within the biochar could serve as a viable quality indicator. Evaluating biochar quality involves assessing three characteristics derived from proximate analysis: fixed carbon, volatile matter, and ash content. These indicators contribute to determining the quality of biochar and can serve as benchmarks when assessing its suitability (Sorrenti et al., 2016; Ruzickova et al., 2021).

Roles and Functions of Biochar in Soil

Biochar serves as a soil amendment and a carrier for nutrients, although it does not function as a fertilizer. However, when biochar is produced from feedstock with relatively high nutrient content, such as ‘manure,’ it may be viewed as a source of fertilizers. Numerous researchers (Yan et al., 2022; Shakoor et al., 2021) have employed biochar and witnessed improvements in soil properties, resulting in enhanced plant growth and increased crop production. When introduced into the soil, biochar delivers three primary benefits: (1) Water Management: Its porous structure operates like a sponge, absorbing and gradually releasing water into the soil. (2) Nutrient Enrichment: It attracts and retains nutrients, acting as a reservoir that supplies both plants and soil biology. (3) Microbial Habitat: Biochar functions as a substrate, offering a habitat and refuge for soil microbes (Lasota et al., 2021; O’Neill et al., 2009; Dey & Mavi, 2022). This supports the increase in organic matter mineralization (Franco et al., 2024) and the subsequent release of nutrients for enhanced plant growth (Kakouridis et al., 2022). The mineralization rate of biochar is considerably less affected by varying mineral contents compared to uncharred organic matter within short timeframes such as several months (Woo et al., 2016). The porous structure of biochar can modify soil physical properties like bulk density, pore space, and water retention (Quin et al., 2014). Moreover, its sorption capacity holds potential for composting processes (Li et al., 2022), offering benefits like reduced nitrogen losses, increased carbon content, and improved compost quality. The value of biochar extends to improving soil microbial populations, with applications including biochar-based bio-fertilizers and serving as a carrier for soil microbial inoculants. Implementing biochar can elevate soil microbial biomass—both carbon and nitrogen—by approximately 25%, while simultaneously reducing the metabolic quotient by 13% (Zhou et al., 2017), thereby indicating an improvement in microbial Carbon Use Efficiency (CUE). Lower microbial quotients correspond to higher CUE, and vice versa.

Biochar boasts a prolonged lifespan in terrestrial environments as a soil conditioner (Schmidt et al., 2018) and serves as a long-term carbon sink for atmospheric carbon dioxide (Shakoor et al., 2021). Its resilience to decomposition by microorganisms renders it an appealing habitat for soil microbes. The heightened microbial population brought about by adding biochar can lead to the generation of ethylene within fresh biochar, which subsequently reduces emissions of N2O and CO2 gases (Wei et al., 2019).

Soil biology improvement following biochar incorporation can be attributed to several factors:

1. Enhanced Nutrient Availability: Biochar facilitates nutrient cycling and availability.

2. Strengthened Microbial Communities: Microbial populations experience enhancement.

3. Augmented Plant-Microbe Signaling: Favorable interactions between plants and microbes.

4. Support for Beneficial Fungi and Bacteria: The porous structure acts as a refuge, safeguarding them from potential predators (Madawala, 2021; Haider et al., 2022). This suggests that microbes generally do not fully consume biochar; instead, they utilize its labile components, residing within it. This beneficially contributes to improved soil fertility and plant vigor.

Biochar also elevates soil porosity by fostering soil aggregation. In addition to increasing water retention, it enhances water availability to plants (Singh et al., 2022; Głąb et al., 2016), covering the range between field capacity (moisture retention at 0.33 bar) and wilting point (moisture retention at 15 bars). Biochar also enhances soil fertility (Ding et al., 2016), positioning it as a favored soil management practice for enhancing soil structure and water retention, ultimately optimizing irrigation management by reducing irrigation requirements (El-Naggar et al., 2019; Ahmadi et al., 2020).

Biochar application enhances soils' physical health by promoting the development of soil structure, consequently leading to amplified crop yields. An improvement in moisture retention capacity is observed (Prasad et al., 2022), which has been measured to exceed 22% (Peake et al., 2014). This intensified crop production can be attributed to enhanced stability in soil aggregates, the mitigation of soil degradation (Karamiet al., 2012), and the shielding of soils from environmental influences.

Biochar can alleviate soil compaction, resulting in a noteworthy 10% reduction in bulk density (Peake et al., 2014). This effect contributes to an increase in soil porosity (Nelissen et al., 2015; Dierks et al., 2021), alongside an augmentation in Cation Exchange Capacity (CEC) by approximately 4-30% and greater nutrient retention capacity (Prasad et al., 2022). It is thus imperative to tailor biochar use to suit different soil types' specific characteristics. The following section delves into a comprehensive exploration of the existing literature on this matter.

Several studies indicate that the incorporation of biochar into soil may not yield a significant impact on water retention and plant availability, particularly in sandy soils (Hardie et al., 2014; Prasad et al., 2022). This outcome can potentially be attributed to the hydrophobic nature of biochar and the variability in application rates. However, there is a wealth of evidence demonstrating an increase in organic carbon within sandy soils following biochar application (Singh et al., 2022), resulting in an improved water supply for plants (Basso et al., 2013; Głąb et al., 2016). Ahmadi et al. (2020) also showcased alterations in the structure of sandy-clay soil due to biochar amendments, thereby influencing water retention. Notably, Conte et al. (2013) and Bubici et al. (2016) elucidated the interaction between hydrophobic biochar and hydrophilic water. Functioning as a soil conditioner, biochar enhances soil tilth, moisture and nutrient retention, biological communities, and mitigates soil acidity (Ahmadi et al., 2020; Dey & Mavi, 2022; Ahmadi et al., 2020). Biochar can potentially mimic the colonization of mycorrhizal fungi, facilitating phosphorous delivery to plants to foster root growth (Dey & Mavi, 2022).

The use of biochar as a soil conditioner to enhance soil health has become well-established. It can be employed either as an independent amendment or in conjunction with compost and fertilizer, tailored to meet specific soil amendment requirements. This integration can cut inputs by up to 30% (Burezq & Davidson, 2021). Biochar application lacks a universal method; it can be directly mixed with soil, sub-soiled, or even combined with fertilizers and strategically positioned beneath seeds for optimal fertilizer efficiency in wheat crops (Burezq & Davidson, 2021). Biochar yields optimal results as a soil amendment when combined with compost. This lets biochar absorb nutrients from the compost, resulting in a synergistic effect that imparts maximum benefits to the soil. There are various biochar application methods, including:

1. Layering in Soil: Biochar can be laid out in soil layers.

2. Mixing with Compost, Manure, or Potting Media: It can be blended with compost, animal manure, or potting media.

3. Combination with Fertilizers: Biochar can be paired with fertilizers to adsorb nutrients for controlled leaching and slow release.

4. Banding in the Rhizosphere: Application around the root zone or rhizosphere of the plant (Pandey et al., 2017) can enhance microbial communities and nutrient availability.

Addressing the challenges of handling dusty biochar is important due to associated health and safety risks. This concern can be mitigated by utilizing biochar slurry, or small biochar granules suitable for earthworm ingestion and soil incorporation. Observations indicate that applying a 1 or 2-inch-thick layer of biochar and thoroughly blending it into the soil can promote root development and prevent erosion caused by wind or water.

To enhance its transport efficiency and as a soil conditioner with extended effects, biochar can be pelletized to increase its density (He et al., 2017). The effects of pelletized biochar may persist longer compared to non-pelletized versions. The creation of biochar pellets involves using a pellet mill or press to achieve different sizes and shapes (Aghalari et al., 2021).

Diverse researchers have documented greater soil aggregation after employing biochar as a soil conditioner. For instance, the incorporation of rice husk biochar was shown to bolster soil aggregation by a range of 8% to 36% (Ahmadi et al., 2020). Notably, the inclusion of biochar in sandy soil yielded a 6% augmentation in water holding capacity at a rate of 1 ton ha^{1}, and a remarkable increase of up to 25% at a rate of 40 tons ha^{-1} (Glaser et al., 2015). In silty loam soil, biochar application led to an 11% rise in water-holding capacity (Zhou et al., 2024). In specific instances, the introduction of 20 tons ha^{-1} of biochar into sandy soil resulted in a notable doubling of plant-available water, subsequently leading to a 100% increase in irrigation efficiency (Cong et al., 2023). This advancement could potentially translate into substantial long-term water conservation.

In developing nations, farmers remain largely unfamiliar with biochar, and its usage is still in its infancy. There is a pressing need to promote biochar adoption within the agricultural community to harness its potential for enhancing crop productivity. To achieve this, it becomes essential to establish economic incentives that encourage farmers to integrate biochar as a means to stabilize carbon on their farms, thereby reaping long-term benefits. The key to garnering farmers' interest in biochar lies in illustrating its utility as a consistent and modest soil input, as opposed to the prevalent norm of a single, high-dose application exceeding 10 tons per hectare (Bolan et al., 2022). It is advised to opt for a lower application rate ranging between 1 to 4 tons per hectare, as excessive dosages may potentially disrupt soil and plant root systems (Pandey et al., 2017). In Kenya, the use of biochar (0.4-8 tons of carbon per hectare) on degraded soils has led to remarkable crop productivity increases ranging from 20% to 220% (Shakoor et al., 2021). In the central Amazon, the application of 8 tons of biochar per hectare has also resulted in a doubling of maize yields (Pandey et al., 2017). In a separate study (Cong et al., 2023), a comparable surge in rice crop yield was observed with an application rate of 8 tons per hectare. Recent research (Hale et al., 2020) conducted on Ultisols in humid tropical soils highlighted that the addition of 22.5 ton ha^{1} of biochar led to a sevenfold increase in dry maize grain yield compared to the control treatment. This promising outcome was sustained over a span of 7 planting seasons, spanning from November 2016 to May 2019. Scientists emphasize the need for ongoing efforts to refine the utilization of biochar on agricultural farms, particularly to derive economic advantages for small-scale farmers. In this context, Zahra et al. (2022) observed a substantial 150-98% increase in maize grain yield through the application of biochar at rates of 15 and 20 tons per hectare, respectively. Singh et al. (2022) determined that a suitable dose of 1% biochar (derived from Eucalyptus camaldulensis) was effective for coarse-textured soils with low buffering capacity, while a dose of 2% was optimal for fine-textured soils with high buffering capacity.

In another investigation (Glaser et al., 2015), the introduction of biochar (1 ton ha^{-1}) alongside mineral fertilizer led to a 20% maize yield increase. When biochar was added at a higher rate of 10 ton ha^{1} to compost, maize yield improved by 26% compared to compost application alone. This demonstrated the enhanced performance of mineral fertilizers and compost when combined with biochar. There have been instances where the use of straw and rice biochar at high rates (>20 t ha^{-1}) for cereal crops did not yield profitability; however, the integration of biochar at the same rate alongside NPK granules contributed to increased farmer income (Clare et al., 2014). Sub-Saharan Africa has also seen positive outcomes from a single application of biochar at a rate of 13 tons/ha for cereal production (Dickinson et al., 2015).

The Priority of Biochar Utilization Compared to Other Organic Amendments.

Biochar holds a distinct advantage in preserving a higher level of stable carbon (50%) when compared to burning (3%) and other forms of biological decomposition or land application, which retain only 10-20% after 5-10 years (Shakoor et al., 2021). The superiority of biochar over compost, manure, and organic fertilizers stems from various factors, including but not limited to the following: i) Biochar is sterilized during production and contains stable carbon, while animal manures and composts may harbor weed seeds, pathogens, and contaminants like heavy metals that could potentially enter the food chain. ii) Unlike manure and compost, which have a relatively short lifespan after being applied to the soil, biochar remains effective for decades to millennia. iii) Decomposing manure and compost release gases such as ammonia and methane, contributing to temperature rise and climate change, while biochar does not emit such gases. iv) Combining biochar with fertilizers transforms them into slow-release fertilizers, enhancing their durability and improving soil fertility (Spokas et al., 2012; Xu et al., 2014; Schmidt et al., 2018; Kammann et al., 2015). v) Biochar can adsorb various nutrients at different levels, including nitrate (3.7%), ammonium (15.7%), and phosphate (3.1%) (Cui et al., 2021). This nutrient adsorption capacity varies based on biochar quality, including pH and functional groups. Ammonium can be retained on biochar through physical adsorption (van der Waals adsorption) on negatively charged surfaces (Zhang et al., 2015; Song et al., 2020). Biochar should not be regarded solely as a nutrient source, but rather as an organic soil conditioner. Its addition improves soil properties, enhances nutrient cycling, and reduces leaching (Peng et al., 2021). Recognizing the moisture and nutrient retention capabilities of biochar, there has been a notable increase in plant nutrient uptake and spring barley grain yield (Hood-Nowotny et al., 2018).

Drawbacks Associated with Biochar.

The favorable impact of biochar on agricultural yield is frequently highlighted as a significant co-benefit of its carbon sequestration. However, there are also instances of negative yield responses. Biochar application in agricultural soils can directly affect soil biota and their functions, leading to reduced crop yields (Wang et al., 2024). This includes reductions in mycorrhizae and total microbial biomass that have been observed following biochar application (Yang et al., 2022). The microbial population decline might be attributed to the presence of heavy metals and other pollutants in the soil (Luo et al., 2023). Luo et al. (2023) noted the influence of charcoal volatile matter content on plant growth and soil nitrogen transformation.

Biochar has diverse effects on crop yield, showing positive effects on highly weathered acidic soils with low CEC and minimal inputs, while demonstrating minimal or even negative effects on temperate soils (Jeffery et al., 2017). Negative yield responses are particularly observed in alkaline soil conditions (high pH soils), which may restrict phosphorus supply to plants (Luo et al., 2023) and result from nutrient deficiencies at higher pH levels (Xu et al., 2014). The presence of sorbed volatile organic carbons (VOCs) on biochar and the generation of free radicals could potentially hinder germination (Ruzickova et al., 2021; Liao et al., 2014).

Biochar, particularly with a high pH, might limit nutrient availability and negatively impact cation exchange capacity (CEC) in soils with high pH (Lahmann & Joseph, 2009). Prior knowledge of soil characteristics is thus essential for effective biochar use; for instance, using high pH biochar on acidic soils (liming effect) and low pH biochar on alkaline soils. Generally, biochar derived from plant material exhibits lower pH values compared to biochar obtained from animal biomass or manure (Ruzickova et al., 2021).

Due to a lack of comprehensive scientific information, the long-term nutrient availability from biochar remains uncertain. Improved growing conditions for crops might intensify weed competition as well (Kavitha et al., 2018), while simultaneously reducing the efficacy of herbicides (Gámiz et al., 2019). One effective approach to enriching nutrients involves co-composting the biochar, which enhances both the biochar and the compost.

Investigating the Potential of Biochar Production from Agricultural Residues and Improving Soil Fertility in the Arab Region

The National Scientific and Technical Information Center (NSTIC) at the Kuwait Institute for Scientific Research (KISR) was consulted to access all relevant databases from the past 15 years concerning the potential of biochar production from agricultural residues and its impact on soil fertility in the Arab region. Based on the gathered data, the following insights were identified:

In Arab countries and the developing world, crop yields tend to be lower than in developed countries. This discrepancy can be attributed to factors such as the lack of access to modern agricultural technologies and essential inputs and challenges in timely input delivery to farms. Consequently, Soil fertility continuously declines due to nutrient and carbon depletion, inadequate water management, and soil erosion. There has been limited investment in maintaining soil fertility as well. Despite these challenges, there are promising opportunities in Arab and developing countries to enhance soil health by transforming agricultural waste into valuable resources, including organic/bio-fertilizers, compost, and biochar, rather than resorting to field burning as a means to prepare land for the next crop.

The Gulf Cooperation Council (GCC) countries, as developing nations, possess substantial capital but grapple with water scarcity and a dearth of arable land. Their sandy and infertile soils necessitate substantial food imports, incurring significant costs. To mitigate these challenges, compost is regularly employed in irrigated fields to sustain productivity; however, compost tends to rapidly mineralize within a short cropping season. Another viable alternative is the adoption of highly stable carbon material, namely “biochar,” to replace easily decomposable organic manure. While many consider biochar to be sterile due to its high-temperature production process, it might be misleading to categorize biochar as sterile if not stored under appropriate conditions, such as a vacuum. The strong microbial stability of biochar arises from its chemical composition, rather than its sterility. In reality, biochar does undergo decomposition, albeit at a typically slower rate than non-pyrolytic organic matter. Further research is warranted to comprehend how biochar impacts the nitrogen cycle and its various reactions (mineralization, nitrification, denitrification, immobilization) in soil over an extended period (Liao et al., 2020; Clough et al., 2013).

The long-term sustainability of soil fertility plays a pivotal role in enhancing food security. Numerous reports highlight the positive impact of incorporating biochar on soil fertility and farm productivity (He et al., 2017; Singh et al., 2022; Allohverdi et al., 2021; Singh et al., 2022). For instance, Singh et al. (2022) demonstrated a 10% increase in plant productivity and over 100% improvement compared to fully fertilized plots (Cong et al., 2023). Dai et al. (2020) also noted enhanced yield predictability, accelerated germination, prolonged cropping seasons, and increased drought resilience in crops. The utilization of a biochar-soil management system can extend to cultivating crops on marginal lands, potentially contribute to disease reduction in crops (Yang et al., 2022), and foster the stimulation of growth-promoting microorganisms or plant hormones (Wei et al., 2019), ultimately leading to elevated crop yields.

The physical, chemical, and biological attributes of soils play a pivotal role in determining the yield potential of various crops and the overall ecosystem health (Alkharabsheh et al., 2021). The introduction of biochar into the soil serves to enhance plant growth by recycling nutrients sourced from animal manures (Kammann et al., 2015; Yang et al., 2022). Biochar is also widely recognized for its effectiveness in sequestering soil carbon and bolstering soil fertility (Vaughn et al., 2015). It can conserve water through improved moisture retention, purify soils by adsorbing heavy metals and pollutants, and elevate crop productivity (Burezq, 2019), thereby offering a range of advantages. While the role of biochar in enhancing soil structure is well-established, its capacity to enhance soil fertility is still being explored. Nevertheless, research has indicated that when biochar is combined with compost, animal manure, and cattle manure, it significantly boosts crop yield across diverse soil types and climatic conditions (Godlewska et al., 2017), presenting a mechanism for nutrient recycling (Kammann et al., 2015).

Various types of feedstock are readily available in developing countries which are suitable for biochar production. Commonly used feedstocks include wood chips, organic wastes, plant residues, and poultry manure (Allohverdi et al., 2021). Materials such as rice husk, empty fruit bunches, peanut shells, wheat straw, orange peels, olive pomace (Hyder et al., 2014; Claoston et al., 2014), sawdust, date palm fronds, cotton stalks, date palm seeds, tree branches, and poultry manure are used as well. Biochar composition is inherently tied to the specific feedstock used, but the resulting biochar product can be enriched with various nutrients to enhance its quality (Table 1).

The date palm (*Phoenix dactylifera L.*) stands as one of the earliest cultivated trees worldwide (Rahman et al., 2022). Its components include leaves/fronds, trunks, date seeds, date flesh, and fruit holders. This study explores the potential of utilizing date palm feedstock for biochar production across 18 Arab countries (Table 2). Within these nations, a total of 82.35 million productive date palm trees cover an area of 880,760 hectares (AOAD, 2008). Each individual date palm tree generates approximately 20 kg of dry biomass (Tahir et al., 2020). Assuming a 35% conversion rate of biochar from date palm feedstock (Igalavithana et al., 2018), it is estimated that these countries collectively possess the capacity to yield 576,422 metric tons of biochar. Through this production, each date palm tree could potentially receive 7 kg of biochar, amounting to 14 kg over 2 years. This quantity might be deemed sufficient for around 5-10 years, after which additional biochar applications could be implemented. The remaining biochar produced from date palm feedstock in subsequent years can be allocated to other crops. Such an approach would help farmers invest in soil health through a "crop-to-soil" investment strategy.

Table 1. Physiochemical properties of different biochars (Alaboudi, 2019)

Feedstock	Temperature	pH	%							CEC, cmolc kg^{-1}	C/N ratio	%		H/C ratio	O/C ratio	SSA, m^2 g^{-1}
			C	N	P	S	Ca	Mg	K			O.M	Ash			
Sugar cane bagasse	<500	8.63	74.02	1.00	0.24	—	0.17	0.32	2.00	69.62	74.02	87.80	12.21	0.42	0.23	92.30
Orange peel	<500	8.75	66.36	2.13	0.25	—	1.04	0.28	1.86	68.28	31.15	88.80	11.17	0.65	0.32	0.20
Oak wood	600.00	6.38	87.50	0.20	—	—	—	—	—	75.70	489.00	—	0.01	0.33	0.07	642.00
Corn stover	350.00	9.39	60.40	1.20	—	—	—	—	—	419.30	51.00	—	11.40	0.75	0.29	293.00
	600.00	9.42	70.60	1.07	—	—	—	—	—	252.10	66.00	—	16.70	0.39	0.10	527.00
Corn stalk	400.00	9.60	51.10	1.34	0.25	—	—	—	1.34	—	38.13	—	—	—	—	—
	500.00	10.10	48.40	0.55	0.44	—	—	—	2.65	—	88.00	—	—	—	—	—
Wheat straw	425.00	10.40	46.70	0.59	—	—	1.00	0.60	2.60	—	79.15	—	20.80	—	—	—
Rice straw	400.00	—	71.30	1.46	—	—	—	—	24.60	—	48.84	—	36.20	—	—	—
Peanut hull	500.00	8.60	82.00	2.70	0.30	0.10	—	—	—	—	30.37	—	9.30	0.44	0.03	200.00
Coco peat	500.00	10.30	84.40	1.02	0.03	0.27	0.06	2.30	—	—	82.75	—	15.90	0.41	0.10	13.70
Coconut charcoal	<500	8.86	76.50	0.20	—	—	—	—	—	—	426.60	—	2.90	0.12	—	—
Pinewood	<500	8.47	53.20	0.40	—	—	—	—	—	—	143.40	—	65.70	0.35	—	—
Eucalyptus deglupta	350.00	7.00	82.40	0.57	0.06	0.03	—	—	—	4.69	144.56	—	0.20	—	0.12	
Hardwood sawdust	500.00	—	63.80	0.22	—	0.01	—	—	—		290.00	—	22.80	0.60	0.14	1.00
Chinese pine	600.00	8.38	66.67	2.21	—	—	—	—	—	31.58	30.17	—	12.50	0.58	0.31	—
Cattle waste	380.00	8.20	62.10	0.10	—	—	—	—	—	39.00	621.00	—	25.60	1.90	0.27	—
Sewage sludge	380.00	8.50	38.30	5.20	—	—	—	—	—	0.50	7.37	—	44.90	0.94	0.25	—

Aside from conducting a comprehensive review encompassing diverse facets of biochar, our study delves into an analysis of its potential within the framework of biochar production in Arab countries, particularly focusing on the utilization of date palm-based feedstock. Notably, the Arab region hosts a staggering 70% of all date palms worldwide at 120 million, with around half concentrated in the GCC nations, Iraq, and Yemen (Rahman et al., 2022). The remainder of this abundance is dispersed across North African countries, including Sudan (Rahman et al., 2022). For perspective, Arab nations collectively possess a significant count of 82.3 × 10ˆ6 productive date palm trees, spanning an extensive area of 880,760 hectares (AOAD, 2008), as illustrated in Table 1. On average, each date palm yields approximately 20 kg of dry fronds annually (Tahir et al., 2020), signifying the substantial volume of feedstock that these countries have at their disposal. However, in the GCC countries, a significant proportion of date palm waste is relegated to landfills, causing significant environmental concerns while simultaneously occupying scarce arable land.

The Kuwait Biochar Initiative (KBI) represents a significant effort in the Arab world, particularly spearheaded by the Kuwait Institute for Scientific Research. This initiative has laid the groundwork for building connections with the International Biochar Initiative and has included early experiments applying biochar on small farms with sandy soils. These trials demonstrated a remarkable 55% increase in fresh alfalfa yields compared to control plots without biochar (Burezq, 2019). The promising outcomes of this research have increased optimism for improving local agricultural production, especially in light of challenges like the COVID-19 pandemic, which disrupted food supply chains in various countries, including GCC members.

These findings have paved the way for the KBI model to be adopted on small farms across Arab countries and other developing nations, promoting crop intensification. This approach aligns with UN Sustainable Development Goal 2, which aims to double the agricultural productivity and incomes of small-scale food producers by 2030. It also emphasizes the establishment of sustainable food production systems and resilient agricultural practices to enhance

Table 2. Number of productive date palm trees and area used in Arab countries (AOAD, 2008)

Country	Number of productive trees	Area occupied by date palm trees (ha)	Total cultivated area (ha)	Date palm fronds (tons) at 20 kg per tree per year	Potential of biochar production (tons) at 35% recovery
Jordan	104,380	660	300,000	2087.6	730.66
United Arab Emirates	16,342,190	219,300	83,830	326,843.8	114,395.33
Bahrain	379,980	1,520	3,730	7,599.6	2,659.65
Tunisia	3,335,800	46,000	4,473,880	66,716	23,350.6
Algeria	10,926,000	159,870	8,494,570	218,520	76,482
Saudi Arabia	12,000,000	155,700	1,136,100	240,000	8,400
Sudan	2,646,000	35,280	28,703,640	52,920	18,522
Syria	72,600	130	5,730,600	1,452	508.2
Iraq	8,024,000	101,500	3,303,750	160,480	56,168
Oman	2,457,000	32,760	156,770	49,140	17,199
Palestine Territories	301,200	300	151,000	6,024	2,108.4
Qatar	335,300	1,440	29,930	6,706	2,347.1
Kuwait	312,210	1,450	15,940	6,244.2	2,185.47
Libya	2,100,000	28,000	2,644,000	42,000	14,700
Egypt	12,039,420	36,450	3,824,040	240,788.4	84,275.94
Morocco	5,760,000	42,000	9,186,500	115,200	40,320
Mauritania	600,000	8,000	336,000	12,000	4,200
Yemen	4,610,000	10,400	1,609,500	92,200	32,270
Total	82,346,080	880,760	70,183,780	1646921.6	576,422.56

land and soil quality gradually. Investing in soil improvement is crucial to increasing crop production, particularly as the global population is expected to reach 9.2 billion by 2050 and require a 70% global food output increase, with even greater growth needed in developing countries (UN-SDG). The KBI emerged from a deep understanding of current soil limitations affecting agricultural yields, contrasted with the insufficient investment in agriculture. Despite the clear benefits of biochar, its adoption by farmers worldwide remains limited, including in Kuwait, where its use is still in the early stages. As part of the KBI, plans are in place to distribute farm-scale biochar production kilns to 50 farmers in each crop zone, enabling them to produce biochar by recycling agricultural residues that would otherwise end up in landfills. This strategy builds on local successes, such as the alfalfa trials conducted by Burezq (2019), and aims to implement the KBI model on small farms in Kuwait while advocating for its adoption in developing countries, particularly in regions like the GCC and Africa, where soil quality poses significant challenges.

Worldwide Biochar Manufacturing

Significant quantities of biochar are being produced in the United States and China. These countries have implemented governmental policies that involve burning straw in fields and providing subsidies for straw collection. As a result, large-scale adoption of biochar for cereal crops and horticulture has occurred, as China illustrates (Thengane et al., 2021). On the other hand, biochar production in several other nations remains under 50,000 tons per year. In China, a substantial proportion of the generated biochar is used to produce biochar mineral NPK granular fertilizers. The recent recognition of the role biochar can play in soil management indicates that this agricultural method is experiencing a resurgence. It has the potential to offer an immediate solution for enhancing soil carbon sequestration, mitigating greenhouse gas emissions, and remediating soil contamination caused by pollutants. Although numerous studies have highlighted both the positive and negative effects of biochar, there is still a considerable amount of research needed to comprehensively understand the conditions under which biochar usage is environmentally benign.

The International Biochar Initiative Organization predicts that by 2050, a significant portion of agricultural residues (approximately 80%) will likely be repurposed into biochar along with being used as an energy source as well (Karami et al., 2012). However, a considerable portion of the currently produced biochar in Australia, Europe, and the USA comes with a price tag exceeding $500 per ton, which many farmers find to be excessively high (Thengane et al., 2021).

Conclusion

The use of biochar made from date palm fronds offers significant opportunities for advancing sustainable agriculture, enhancing soil health, and protecting the environment. This approach provides an innovative solution for managing agricultural waste by transforming it into a valuable resource instead of allowing it to contribute to pollution. Producing biochar not only sequesters carbon to reduce greenhouse gas emissions but also improves soil fertility and water retention, making it particularly beneficial in arid and semi-arid regions. Its high porosity enhances soil aeration and nutrient retention, potentially leading to increased crop yields and reduced dependence on chemical fertilizers.

Biochar is capable of immobilizing heavy metals and reducing soil pollutants, offering an innovative approach to remediating contaminated soils and supporting ecological restoration. Biochar research is crucial for its potential to tackle urgent global issues like food security, climate change, and sustainable waste management. Several factors, such as feedstock variations and pyrolysis conditions, can influence biochar properties, creating a complex landscape that requires further exploration. Future research should focus on optimizing production methods to tailor biochar characteristics for specific agricultural applications. Furthermore, understanding the long-term impact of biochar on soil microorganisms, nutrient cycling, and soil fertility will be essential to understanding its potential. Investigating how biochar interacts with other soil fertilizers, along with its role in carbon sequestration, could pave the way for integrating this technology into circular economy models. This, in turn, may lead to scalable, sustainable practices that support global agriculture.

Resumen

H. A. Burezq. 2024. Producción sostenible de biocarbón a partir de palmeras datileras: un análisis de soluciones para las regiones árabes. Int. J. Agric. Nat. Resour. 157-175. Esta revisión de alcance investiga el potencial del biocarbón de palma datilera para la agricultura sostenible en las naciones árabes. El análisis revela que los 82,35 millones de palmeras datileras en 18 países árabes podrían producir 576.423 toneladas de biocarbón al año, ofreciendo un recurso importante para mejorar la sostenibilidad del suelo. Este estudio examina sistemáticamente la literatura existente sobre la producción de biocarbón de palma datilera, su impacto en la salud del suelo (incluida la conservación del agua y los nutrientes), los métodos de aplicación óptimos y su potencial para mejorar la seguridad alimentaria en regiones áridas. Los hallazgos resaltan los beneficios económicos y ambientales del biocarbón, particularmente para los pequeños agricultores, y analizan la Iniciativa de Biocarbón de Kuwait como un modelo exitoso para una adopción más amplia de esta práctica agrícola sostenible. La revisión concluye enfatizando el potencial global del biocarbón de palma datilera para la agricultura sostenible y la salud del suelo.

Palabras clave: Agricultura sostenible, biocarbón, enmiendas orgánicas, palmera datilera, pirólisis, revisión del alcance, seguridad alimentaria, sostenibilidad del suelo, suelos arenosos.

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