

Production of Biochar from Cotton Stalks Using the Cone-Pit Open Earth Kiln Technique

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INTRODUCTION

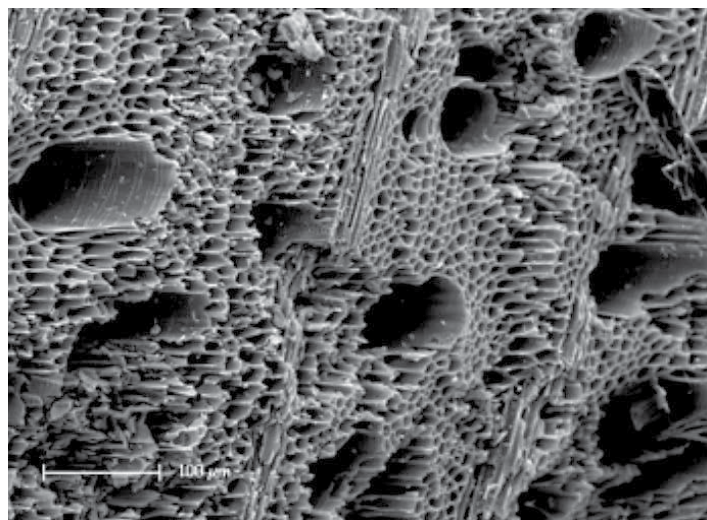
Biochar is charcoal derived from biological material or biomass through incomplete combustion or incomplete burning or controlled pyrolysis. The production of biochar from biomass and its utilization for energy or agricultural purposes is not a novel technology. Our ancestors were aware of the tremendous potential of biochar in transforming their soils into highly fertile and productive lands. They achieved this by producing charcoal from plant matter and incorporating it into the soil, resulting in remarkable agricultural productivity. Notably, the production and use of biochar have been practiced by humans for over 2500 years, particularly in the Amazon basin, where it has been extensively employed as a soil amendment to revive unproductive soils and foster sustainable agriculture, supporting community settlements. Additionally, biochar-enriched soils have been discovered in Ghana, Nigeria, Liberia, Benin, Indonesia, Japan, Ecuador, Peru, and various other parts of the world, potentially formed through natural processes like forest fires, independent of human intervention. In addition to its agricultural benefits, biochar plays a crucial role in carbon sequestration by actively removing carbon dioxide from the atmosphere. In recent times, biochar has been declared as one of the most promising strategies to combat climate change apart from its crucial role in agriculture by improving soil health as a soil amendment (IPCC, 2022; Mousavi et al., 2023).

Figure-1. Biochar



The production of biochar involves utilizing various agricultural residues, including maize stalks, cotton, sunflower, and more. When these feedstocks are converted into biochar, the resulting product possesses a high carbon content, which supports the growth of beneficial soil microbes, as depicted in the accompanying image. Furthermore, the porous structure of biochar enhances soil quality by improving water retention, increasing nutrient availability, and providing a favorable habitat for soil microorganisms.

Figure-2. Biochar has a highly porous structure. Source: Glodowska and Lyszcz, 2012. Biochar under a microscope, Brownsort, UK Biochar Research Centre. From: <http://www.nanoassociates.com/biochar/>



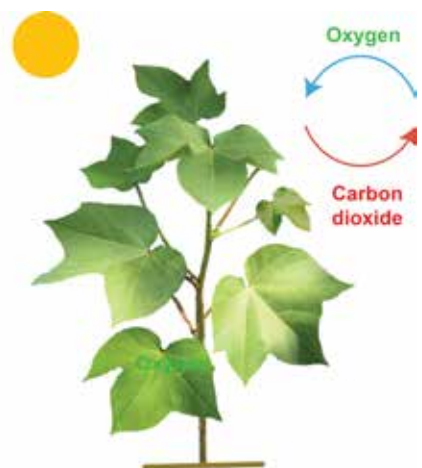
Plants capture atmospheric carbon dioxide (CO₂) for photosynthesis, but most of this captured CO₂ is released back into the atmosphere due to human activities such as burning of crop residues. In many regions worldwide, the common practice of preparing land for a new crop involves the slashing and burning of crop residues and agricultural waste. Unfortunately, this process contributes to environmental pollution through the release of CO₂ into the atmosphere. When cotton stalks or any such crop residues are burned, most of the carbon fixed by plants is released back into the atmosphere as CO₂. Similarly, when plants die, microorganisms break them down, causing approximately

96% of the carbon to return to the atmosphere as carbon dioxide (CO₂). Consequently, in the natural carbon cycle, only a small fraction of the captured carbon, usually less than 4.0%, is sequestered in the soil over a few years, while the majority is emitted back into the atmosphere. Converting crop residues into charcoal, which is called biochar, disrupts this process of biomass degradation and instead fixes the carbon into the soil, where it remains stored for hundreds and even thousands of years thereby slowing down climate change. This critical process is known as carbon sequestration. Biochar is considered a powerful carbon sink that provides us with effective strategies to combat climate change and mitigate carbon dioxide emissions. Therefore, ideally, instead of burning, the biomass should be either incorporated back into the soil through slashing or converted into biochar, which allows for the sequestration of carbon and improvement of soil health. Converting crop residues and farm waste into biochar can mitigate the negative environmental impacts associated with the burning of biomass and promote sustainable carbon management.

Figure-3. Slash and charring of cotton stalks and crop residues.

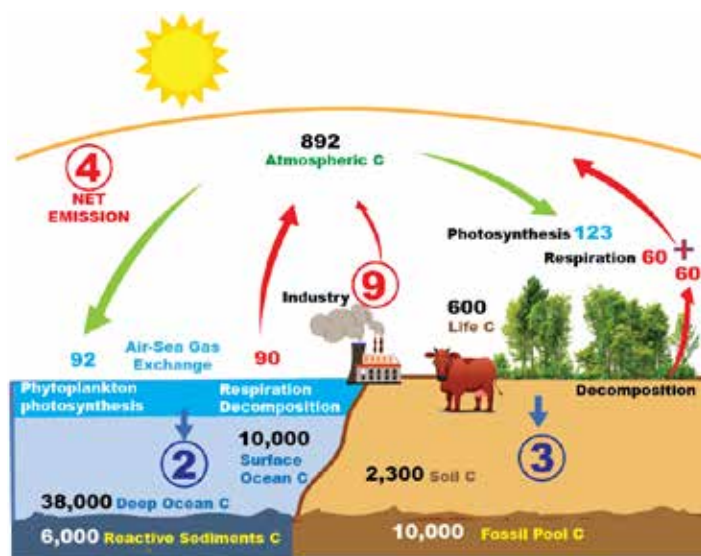


Figure 4. Plants capture atmospheric carbon dioxide for photosynthesis and release oxygen in the process.



The potential impact of returning crop residues back to the soil or converting crop waste from the 1.86 billion hectares of crop land on Earth into biochar is immense. By doing so, it would be possible to address two significant challenges: reducing greenhouse gas emissions resulting from the burning of crop residues and improving soil health. Firstly, returning crop residues to the soil instead of burning them helps to minimize greenhouse gas emissions. Burning crop residues releases CO₂ into the atmosphere, contributing to climate change. By incorporating these residues back into the soil or converting them into biochar, makes it possible to effectively sequester carbon, reducing the amount of CO₂ released into the atmosphere. Secondly, utilizing crop residues for soil amendment, such as through biochar production, enhances soil health. Biochar improves soil structure, water retention, nutrient availability, and microbial activity, leading to increased agricultural productivity and resilience. Such a transformation could play a vital role in achieving net-zero carbon emissions or even carbon neutrality by effectively neutralizing the approximately 4.0 giga tonnes (Gt) or billion tons of carbon that get added to the atmosphere each year due to human activities. By harnessing the carbon sequestration properties of biochar and implementing widespread adoption of this technique, it will be possible to mitigate the detrimental effects of carbon emissions and make significant strides towards a more sustainable future.

Figure 5. Carbon cycle in climate change. Data source: https://en.wikipedia.org/wiki/Carbon_cycle



The main purpose of this article is to highlight an extraordinarily simple technique called 'cone-pit open-earth kiln' that enables the conversion of organic biomass into biochar in-situ without the need for any additional cost, equipment, machinery or infrastructure.

This article is inspired by the invention of the Kon-Tiki pyrolysis method by Prof. Schmidt and Taylor and an article 'How to make biochar with a match' by Josiah Hunt that represent significant breakthroughs, enabling low-cost on-farm production of biochar. The method described here is an adaptation inspired by

their pioneering work, specifically from the research article titled “Kon-Tiki flame curtain pyrolysis for the democratization of biochar production,” authored by Schmidt and Taylor and published in the *Ithaca Journal* in 2014 and the web post by Josiah Hunt <http://pacificbiochar.com/how-to-make-biochar-with-only-a-match/>. Their innovative approach has paved the way for more accessible and affordable biochar production, making it feasible for in-situ mass production and for a broader range of agricultural applications.

A brief history of biochar

The oldest record of use biochar by stone age humans was dated older than 38,000 years in the cave charcoal drawings of Grotte Chauvet (Antal and Gronli, 2003). However, the earliest use of biochar in agriculture may have started much later about 3000 years ago in central America. The story of biochar begins to unfold in 1542 when the Spanish conquistador Francisco de Orellana and his expedition ventured into the Amazon in search of the legendary city of gold, El Dorado. During their journey, they encountered a densely populated settlement thriving on fertile lands. Orellana described a lost city with deep, black, and highly fertile soils, which could potentially be the first account of what is now known as Terra Preta, meaning “black earth.”

Figure-6. The spanish explorer Francisco de Orellana



The significance of Terra Preta gained attention in 1868 when American geologist James Orton and Canadian geologist Charles Hartt became fascinated by this lost city with its extraordinary

black fertile earth. In 1878, British geologist Barrington Brown published a scientific report, and it is believed that he coined the term ‘Terra Preta.’ Subsequently, various scientists such as Felisberto Camargo, Cunha Franco, Johannes Lehmann, Stephen Joseph, and Genxing Pan took a keen interest in Terra Preta.

Figure-7. Prof. Wim Sombroek (Source: <http://biochar.info>)



However, in the 1950s, Dr. Sombroek was one of the first to recognize the carbon sequestration potential of Terra Preta and its connection with biochar. He was captivated by the consistently high fertility of Terra Preta soils, which supported abundant yields over centuries without the addition of synthetic fertilizers. Dr. Sombroek began investigating the reasons behind the exceptional fertility of Terra Preta soils. His findings revealed that the high soil organic carbon content in these black soils was responsible for enhanced nutrient retention, increased cation exchange capacity, and consequently, elevated yields.

Figure-8. Soils in Terra Preta. To the left is the profile of Terra Preta soils with black carbon rich biochar up to two meters depth. (Glaser et al., 2001)

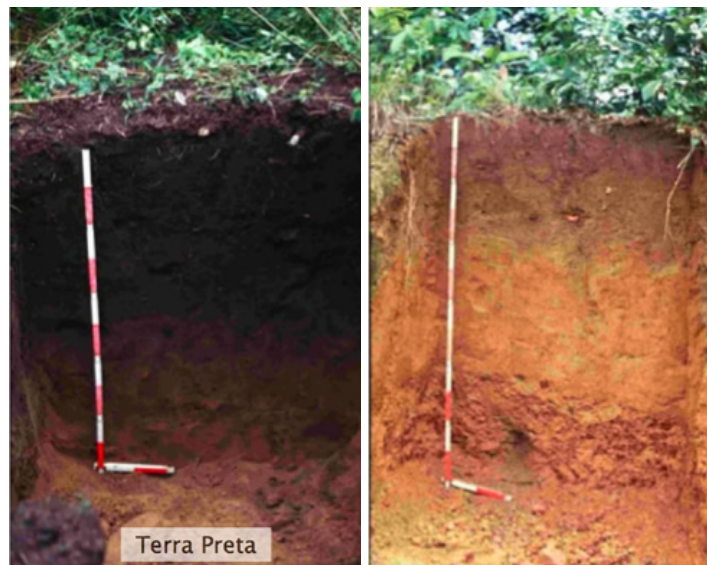
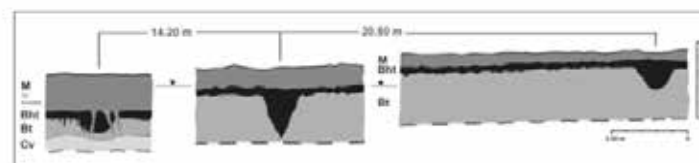


Figure-9. Conical pits in soil west of Cologne (from: Gerlach et al., 2012)



Studies conducted about 30 years ago indicated that the indigenous people of the Amazon region may have created the most fertile Terra Preta soils by incorporating biochar into initially infertile soils. Subsequently, Dr. Glaser confirmed that charcoal, a form of biochar, played a pivotal role in stabilizing soil organic carbon and enhancing nutrient retention. Building upon this research, the first field experiment was established in the Brazilian Amazon in 2001 to replicate Terra Preta and investigate the effects of biochar on soil fertility. It is estimated that the creation of Terra Preta soils covers approximately 1.8 million hectares in the Amazon region of Brazil, serving as a testament to the profound impact of biochar and its potential to enhance soil fertility and productivity.

Biochar production technologies

Biochar has traditionally been produced in many countries through the process of burning stacked wood under controlled, oxygen-limited conditions.

However, this method often results in significant smoke generation and air pollution, with CO₂ emissions accounting for more than half of the biomass burned.

Figure-10. Different kiln designs for biochar production.

Source: <https://biochar.international/guides/biochar-reactor-to-meet-needs/>

In recent years, newer methods of biochar production have been developed to minimize pollution while maximizing biochar yield. These advanced techniques aim to optimize the production process, ensuring efficient conversion of biomass into biochar while minimizing environmental impact. Over the past 25 to 30 years, various machines and equipment have been developed to convert biomass into biochar. Some examples include microwave reactors, hydrothermal reactors, pyrolysis reactors, carbonization furnaces, gasification equipment, and double-walled kilns.

These machines have demonstrated the production of high-quality biochar but faced challenges when it came to scaling up for large-scale production. Despite the existence of several kiln designs, widespread adoption for agricultural use has been limited due to the high costs associated with infrastructure and the challenges involved in transporting either the kiln to the farm or the biomass from the farm to the processing facility.

Kon-Tiki

A significant breakthrough in simple biochar production technology came with the invention of the Kon-Tiki pyrolysis reactor by Dr. Hans Peter Schmidt and Dr. Paul Taylor from the Ithaca Institute. Kon-tiki is a conical shaped metal structure, generally 2 meters wide and about 1.0 to 1.5 meters deep. The design of the Kon-Tiki reactor is inspired by traditional cone structures used in Hindu prayers and charcoal-making techniques employed in Africa. The reactor takes the form of a cone-shaped metal drum with a perforated grate at the bottom. Feedstock, such as wood chips or agricultural waste, is loaded into the drum in layers, ensuring that the lower layers are deprived of air during combus-



tion and undergo a combination of aerobic and anaerobic pyrolysis, ultimately transforming into biochar. The name “Kon-Tiki” was chosen for the reactor in reference to the Kon-Tiki raft, which was used by Norwegian adventurer Thor Heyerdahl to cross the Pacific Ocean in 1947. The reactor, like the raft, floats on top of the feedstock during the biochar production process.

Figure-11. Kon-tiki (Schmidt and Taylor, 2014)



The Kon-Tiki reactor, along with the cone-pit open-earth kiln proposed by Schmidt and Taylor, holds significant potential to become popular as low-cost options for small-scale biochar production, particularly in developing countries where the expense of machinery and transportation to farms can be prohibitive. The Kon-Tiki method has recently emerged as one of the most practical and popular approaches for biochar production. This method stands out with its minimal carbon emissions and is likely one of the fastest methods available to date. The Kon-Tiki method is user-friendly, easy to operate, and cost-effective, making it highly accessible for a wide range of users. However, it is important to note that implementing this method requires some initial investment, and the equipment needs to be transported to the site of biochar production.

Cone-pit open-earth kiln

A young American agriculturist, Mr. Josiah Hunt, played a pivotal role in providing a crucial breakthrough in 2008. It is intriguing to note the paradox that the cone-pit open earth kiln technology, originally invented by our ancestors over 2500 years ago, has only been rediscovered in the past decade by this young American farmer.

The cone-pit open earth kiln technology is remarkably simple yet possesses the power to be scaled up for large-scale, in-situ production of biochar from farm waste and crop residues. Josiah Hunt's contributions have brought this ancient technique back to the forefront, offering immense potential for sustainable biochar production. These innovative ‘Kon-tiki’ and ‘cone-pit open-earth’ technologies, offer accessible and affordable solutions to promote biochar production and its potential benefits in various communities.

Figure-12. Mr. Josiah Hunt. Source: <https://pacificbiochar.com>



Figure-13. Cone-pit open-earth kiln. Source: <https://pacificbiochar.com>



Table-1. Carbon stocks and carbon fluxes in atmosphere, earth and oceans (Giga tons: Gt). Data source: https://en.wikipedia.org/wiki/Carbon_cycle.

	Carbon Reserves (Gt)	Annual absorption of carbon from atmosphere (Gt)	Annual emission of carbon into atmosphere (Gt)	Net carbon sequestration (Gt)
Atmosphere	892			
Ocean surface	10,000			
Deep ocean	37,000	92	90	2
Soils and plants	2,300	123	120	3
Ocean sediments	6,000			
Earth fossil pool	10,000			
Plant biomass	550			
Anthropogenic			9	

Carbon capture and sequestration

The Carbon Cycle Institute, (2020) states that “*agriculture is the one sector that has the ability to transform from a net emitter of CO₂ to a net sequester of CO₂ —there is no other human managed realm with this potential*”. Plants play a crucial role in preserving our planet by sequestering carbon from the atmosphere. Plants absorb CO₂ from the atmosphere and convert it into food for humans and other living organisms. However, all the carbon that plants absorb from the atmosphere is fixed into the soil; majority of it is released back into the atmosphere. Estimates show that more than 96.0% of absorbed CO₂ is subsequently emitted back into the atmosphere due to plant respiration, plant biomass decay and to some extent due to burning. Different estimates may vary (see table-1), the official report of the Inter-governmental panel on climate change (IPCC, 2021) estimates that forests and plants absorb 142 Gt (giga ton = billion ton) of carbon from the atmosphere for photosynthesis and release 136.7 Gt back into the atmosphere through respiration, decay and burning sequester to sequester a net 5.3 Gt of carbon every year into the soils. The global forest land acreage is 4.06 billion hectares and cropland area at 1.86 billion hectares (USGS, 2019). Estimates (Harris et al., 2021) show that between 2001-2019 global forests were a net carbon sink of -2.07 Gt carbon yr⁻¹, reflecting a balance between gross carbon removals (-4.25 Gt carbon yr⁻¹) and gross emissions from deforestation and other disturbances (2.207 Gt carbon yr⁻¹). Agricultural ecosystems have a potential to store up to 1 Gt of soil carbon yr⁻¹ (Sanderman and Baldock, 2010; Abdullahi et al., 2018), which would offset about 10% of the annual GHG emissions estimated at 10 Gt of soil carbon yr⁻¹. Thus, agricultural ecosystems are considered as net sequesters of carbon.

According to the IPCC (2022) assessment, biochar has a global potential to eventually remove 2.6 billion tons CO₂ every year, due to several benefits that include enhanced resilience to climate change, increased soil water-holding capacity, enhanced nitrogen use efficiency and biological nitrogen fixation that

leads to increased yields and food production particularly in sandy and acidic soils. Apart from the benefits to agriculture, biochar has the potential to reduce GHG emissions that are released annually as about 38.0 million tons (Mt) of carbon dioxide equivalent (CO₂e) GHGs (10.2 million tons of carbon) due to burning of crop residues and 192 million tons CO₂e (52.2 million tons of carbon) that are emitted due by crop residues (IPCC, 2022).

Carbon sequestration potential

Addressing the carbon sequestration potential through the conversion of cotton stalks into biochar is important. Biochar carbon sequestration potential is in the range of 21.3%–32.5% (Windeatt, et al., 2014). The carbon content in raw cotton stalks is 41.15% (Venkatesh et al., 2013) to 47.05% (Al Afif et al., 2019). Conversion of raw stalks into biochar at 350-400°C resulted in biochar yields of 20.4% to 46.5% (Al Afif et al., 2020) by weight which contained 58.7% to 71.0% carbon (Venkatesh et al., 2013). Anaerobic pyrolysis of one ton of cotton stalks could result in about 200 to 465 Kg of biochar, which could contain about 130 to 302 Kg carbon, which represents sequestration of 476 to 1109 Kg of CO₂. Therefore, it may be safe to assume that conversion of one ton of cotton stalks into biochar could result in sequestration of about 500 to 1000 Kg CO₂. Globally, the cotton crop produces 26.0 million tons (Mt) of fiber by absorbing about 99.80 of carbon from the atmosphere, which is equivalent to 366 Mt of CO₂. Presuming that all cotton stalks are converted to biochar, a conservative estimate at 50% conversion efficiency shows that at least 84.02 Mt CO₂ can be effectively sequestered into the soil (Table-3).

Table-2. Potential of carbon sequestration by cotton stalk biochar (Million tons)

	Biomass Mt	Carbon content %	Carbon Mass Mt	CO ₂ Mt	Carbon in bio-char Mt	CO ₂ in biochar Mt
Fibre	26	0.44	11.44	41.95		
Seeds	39	0.5	19.5	71.5		
Stalks	97.5	0.47	45.83	168.0	22.92	84.02
Roots	49	0.47	23.03	84.44		
Total	211.5	0.47	99.8	365.9	22.92	84.02

Biochar from Cotton Stalks

Cotton stalks serve as an excellent feedstock to produce biochar. In many countries, cotton stalks are often considered waste materials and are either burned in the field, used as firewood, or simply left stacked near bunds where they decompose. However, these practices have several drawbacks. Burning cotton stalks contributes to air pollution by releasing CO₂ emissions, while stacking them near bunds can facilitate the spread of insect pests and pathogens. Additionally, crop residues such as boll rinds and residual seed-cotton may harbor larvae or pupae of pink bollworm or other insects. Thus, by converting cotton stalks into biochar, we can effectively eliminate residual insects

and pathogens, apart from sequestering significant amount of carbon from farm waste. Conversion of carbon biomass to biochar carbon leads to sequestration of about 50% of the initial carbon compared to the low amounts of about 3% retained after burning and biological decomposition which could be <10–20% after 5–10 years, therefore yielding more stable soil carbon than burning or direct land application of biomass (Lehmann et al., 2006).

Cotton stalks in Africa

Every year, Africa produces an estimated 13 million tons (Mt) of cotton stalks. Unfortunately, when these stalks are burned, it results in the instantaneous release of 22 Mt of CO₂ into the atmosphere. Similarly, the practice of slashing cotton stalks and incorporating them into the soil leads to the release of 21 Mt of CO₂. These emissions highlight the urgent need for alternative and sustainable approaches, such as biochar production, to effectively manage and mitigate the carbon footprint associated with cotton farming in Africa. By converting 13 Mt of cotton stalks into biochar, an impressive 15–16 Mt of CO₂ (equivalent to 4.1 tons of carbon) can be effectively sequestered into the soil.

Cotton stalks in Asia

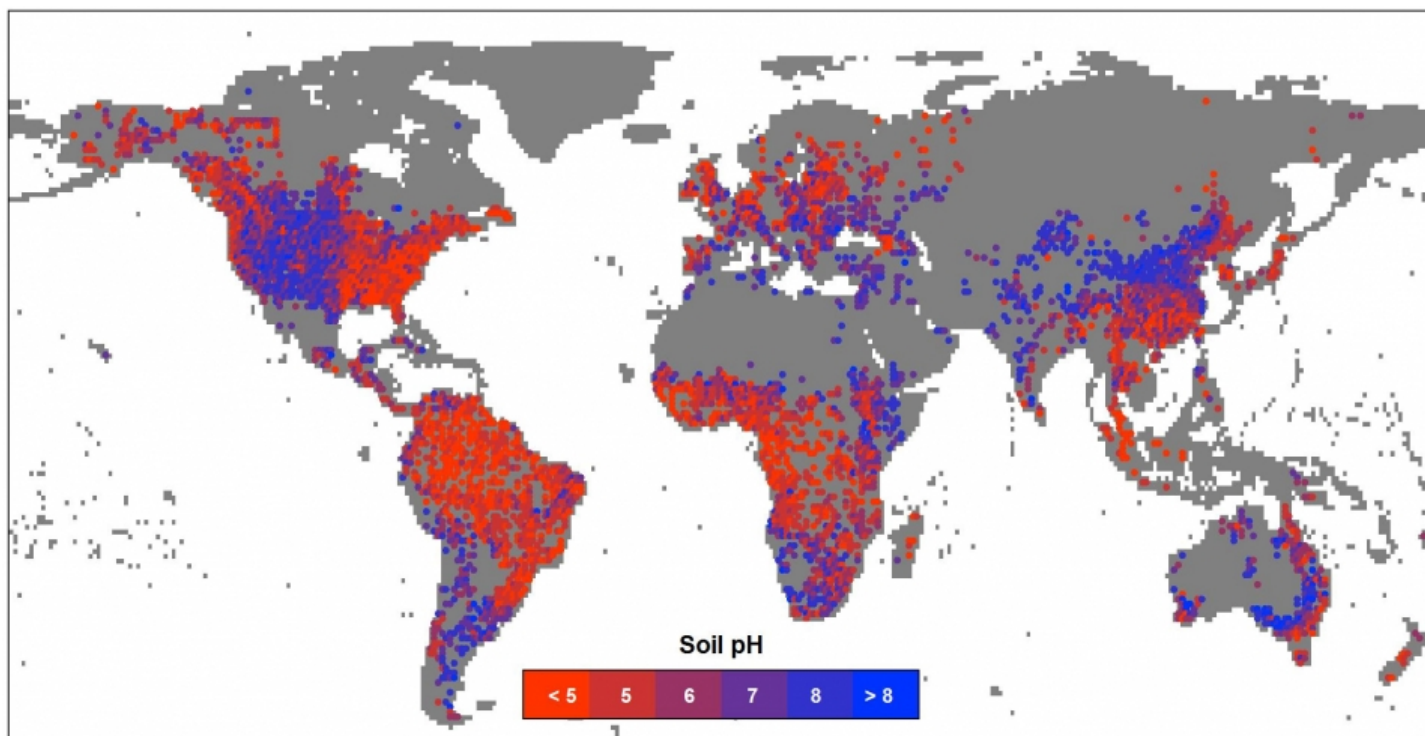
Asian countries such as Bangladesh, India, Myanmar and Pakistan together produce about 68 Mt cotton stalks out of which an estimated 37 Mt of cotton stalks are either burnt in fields or used as firewood; both processes release about 63 Mt of CO₂ into the atmosphere. Converting the 37 Mt of cotton stalks into biochar could effectively sequester 12 Mt of carbon which is equivalent to 44 Mt of CO₂ fixed into the soil. This transformative process

has the potential to make cotton farming climate-positive, surpassing the goal of achieving net-zero emissions. Furthermore, the adoption of biochar has shown to significantly and sustainably increase crop yields, further enhancing the overall productivity of cotton farming operations.

Relevance for Africa

Poor soil health invariably leads to poor crop yields. Africa has lowest cotton yields in the world. Unfortunately, Africa experiences notably low crop yields, with its cotton yields being the lowest worldwide. The degradation of soils is widely believed to be a significant factor behind these low yields. Majority of African soils in the cotton growing regions are acidic with high bulk density and with low cation exchange capacity (CEC); all of which lead to low yields of cotton and other crops. Biochar possesses remarkable qualities that make it a potential solution for remediating degraded soils in Africa. Biochar produced from cotton stalks possesses alkaline properties, has high CEC and very low bulk density. One significant attribute of biochar is its alkaline nature, which allows it to effectively address soil acidity when produced from various crop residues. Additionally, biochar exhibits a high CEC, enabling it to enhance the soil's ability to retain essential nutrients such as potassium, calcium, and magnesium. This exchange process involves the biochar supplying these nutrients to plant roots in exchange for hydrogen ions. Biochar is highly porous and offer immense benefits to improve soil structure by reducing bulk density and increasing water holding capacity of soils. Thus, by incorporating biochar made from cotton stalks into the soil, a significant positive impact can be achieved, resulting in improved soil health and conditions for

Figure-14. Global soil pH map. Source: <https://phys.org/news/2016-12-global-soil-ph-illuminate-climates.html>



agricultural productivity in Africa.

Considering the prospects of biochar and its feasibility in the African context, it is important to explore its applicability in various agricultural systems across the continent. Factors such as availability of feedstock, cost-effectiveness, scalability, and compatibility with local farming practices need to be carefully evaluated. By harnessing the benefits of biochar and adopting suitable production and application methods, African farmers could improve soil fertility, enhance nutrient retention, and ultimately increase agricultural productivity in a sustainable manner.

Figure-15. Soil pH map of Africa. Most African soils are acidic. Source: <https://www.agric.wa.gov.au/soil-acidity/effects-soil-acidity?page=0%2C1>

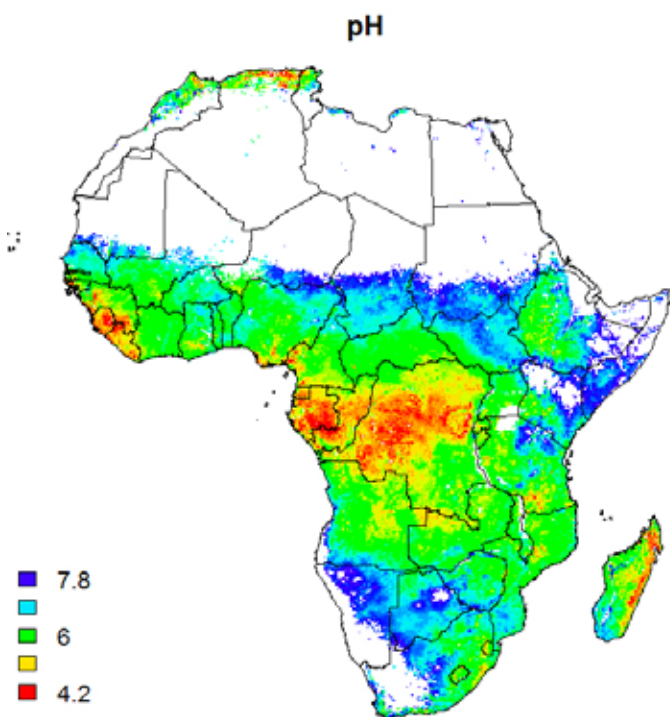
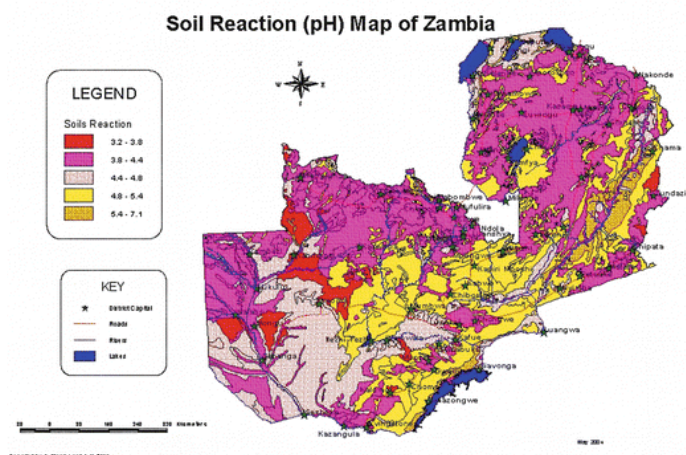


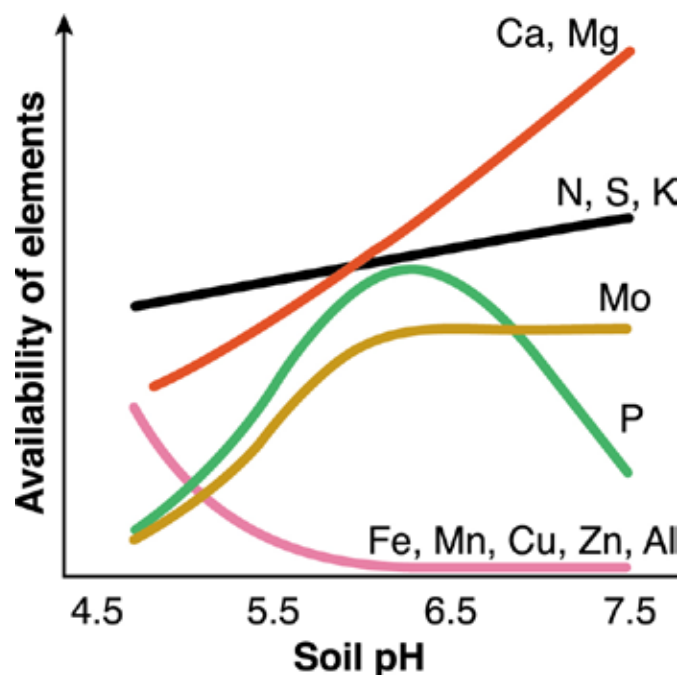
Figure-16. Soil pH map of cotton growing regions in Zambia (Lungu, 2015)



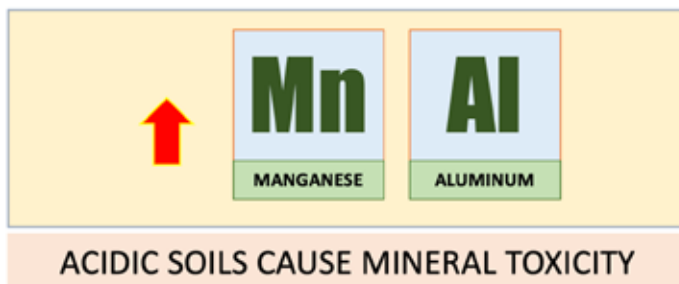
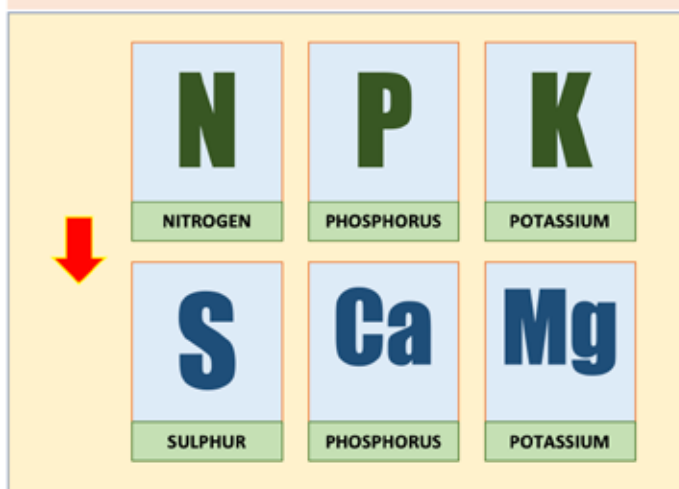
Acidic soils in Africa

The presence of red and reddish dots on the map (Figure-14) indicates the prevalence of acidic soils throughout Africa.

Figure-17. Acidic soils cause nutrient deficiencies. Source: <https://www.agric.wa.gov.au/soil-acidity/effects-soil-acidity?page=0%2C1>



ACIDIC SOILS CAUSE NUTRIENT DEFICIENCY



For example, in the cotton growing regions of Zambia, it is evident from the yellow regions in the south and eastern parts that the soils tend to be acidic.

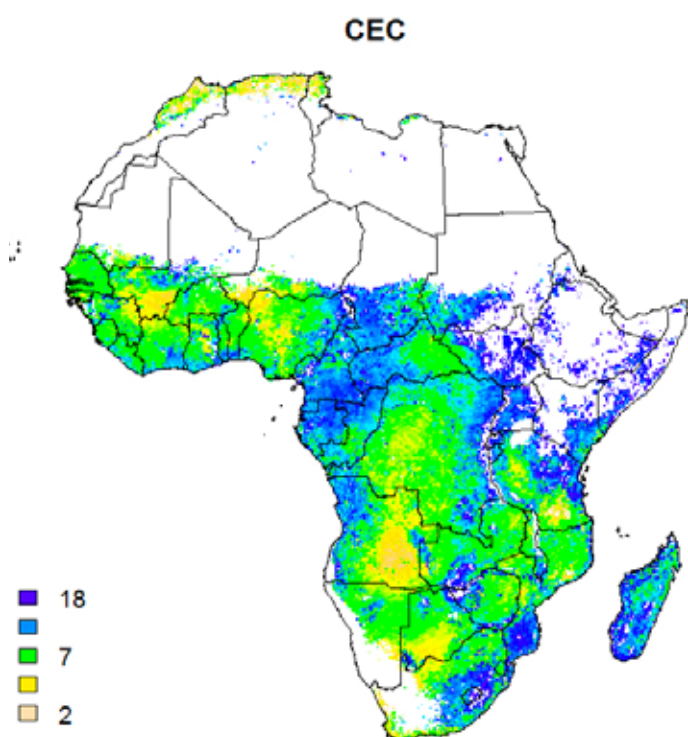
Soil acidity contributes to low yields unless large quantities of synthetic fertilizers are applied. In acidic soils, low crop yields can be attributed to the reduced availability of essential nutrients for plant growth.

Acidity hampers the accessibility of major nutrients like nitrogen, phosphorus, potassium, as well as secondary nutrients like sulfur, calcium, and magnesium. Additionally, acidity triggers the release of manganese and aluminum, which negatively affects root development and growth.

Therefore, the deficiency of crucial nutrients and the accumulation of harmful minerals adversely impact plant health, ultimately resulting in decreased yields. Acidic soils, if not neutralized with lime or adequately supplemented with high levels of fertilizers, typically result in low crop yields.

Unfortunately, the cost of lime and synthetic fertilizers poses a significant challenge in Africa, where prices are notably high compared to other regions. For instance, a bag of urea costs around 3.5 dollars in India, whereas the average cost in Africa exceeds 50 dollars. As a result, the affordability of synthetic fertilizers and other chemical remedial measures becomes a major obstacle for farmers in the region.

Figure-18. Soil CEC of African soils. The yellow and greenish regions represent soils with low CEC. Source: The blue and purple regions represent soils with high CEC. <https://www.isric.org/projects/africa-soil-profiles-database-afsp/newgeneration>

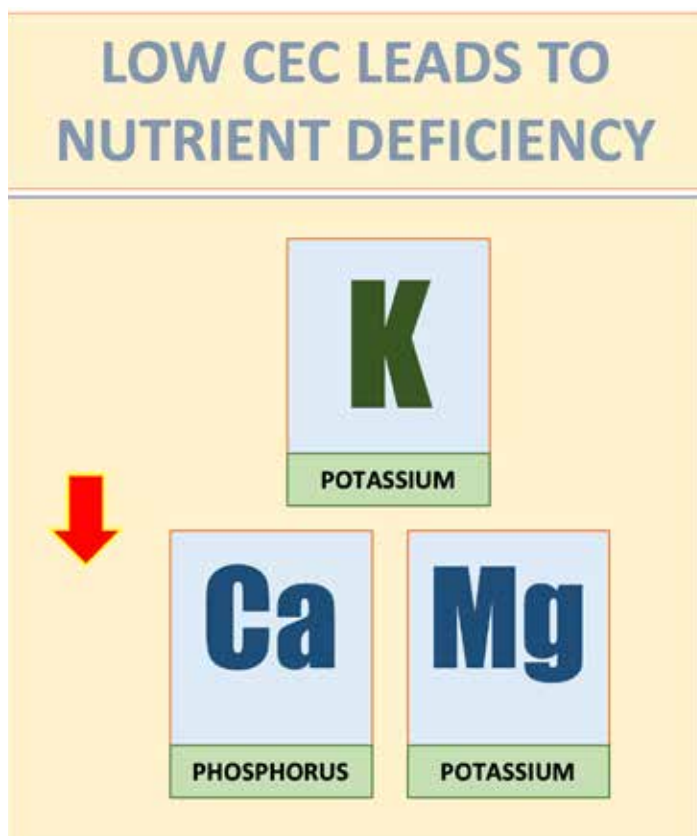


Low CEC in African soils

Unfortunately, acidic soils are often characterized by a low CEC. Soils which have low CEC struggle to retain essential nutrients like potassium, calcium, and magnesium, which could be exchanged with hydrogen ions by plant roots.

The deficiency of these vital nutrients within the soil directly impacts crop yields, resulting in suboptimal agricultural productivity. African soils often exhibit low CEC, which contributes to deficiencies in essential nutrients such as potassium, calcium, and magnesium (Figure 18a).

Figure-18a. Nutrient deficiencies caused due to low CEC



This inadequacy of crucial nutrients directly correlates with low crop yields in these regions.

The low CEC of African soils hinders their ability to retain and exchange these vital elements with plant roots, ultimately affecting plant growth and productivity.

Addressing the CEC limitations and ensuring an adequate supply of potassium, calcium, and magnesium is crucial for improving soil fertility and increasing agricultural yields in Africa.

Biochar derived from cotton stalks demonstrates an impressive CEC, indicating its potential to enhance the CEC in African soils. Incorporation of biochar into soils with low CEC has been shown to enhance the CEC.

These properties make biochar a promising soil amendment for agricultural practices in Africa.

High bulk density of African soils

Soils with high bulk density cause poor root growth and low nutrient availability. In many cotton-growing countries in West Africa and Southeast Africa, the soils commonly exhibit high bulk density, meaning they are less porous and more compact that significantly impacts root growth and subsequently leads to low crop yields.

Soil compaction not only limits root development but also weakens microbial activity and overall crop health. Additionally, high bulk density adversely affects various soil characteristics, including water infiltration, erosion susceptibility, waterlogging, aeration, and water movement within the soil profile. Consequently, during periods of drought, these soils are particularly prone to crop failures.

Biochar, with its porous and lightweight structure, offers the capacity to improve soil structure by reducing bulk density. This structural improvement facilitates better nutrient and water retention within the soil, benefiting plant growth and overall soil health.

By utilizing biochar as a soil amendment, African farmers have the potential to mitigate soil acidity, enhance nutrient availability, and improve soil structure.

These factors collectively contribute to increased agricultural productivity and resilience in the face of challenging environmental conditions.

Figure-19. Soil bulk density map of Africa. Source: <https://www.isric.org/projects/africa-soil-profiles-database-afsp/newgeneration>

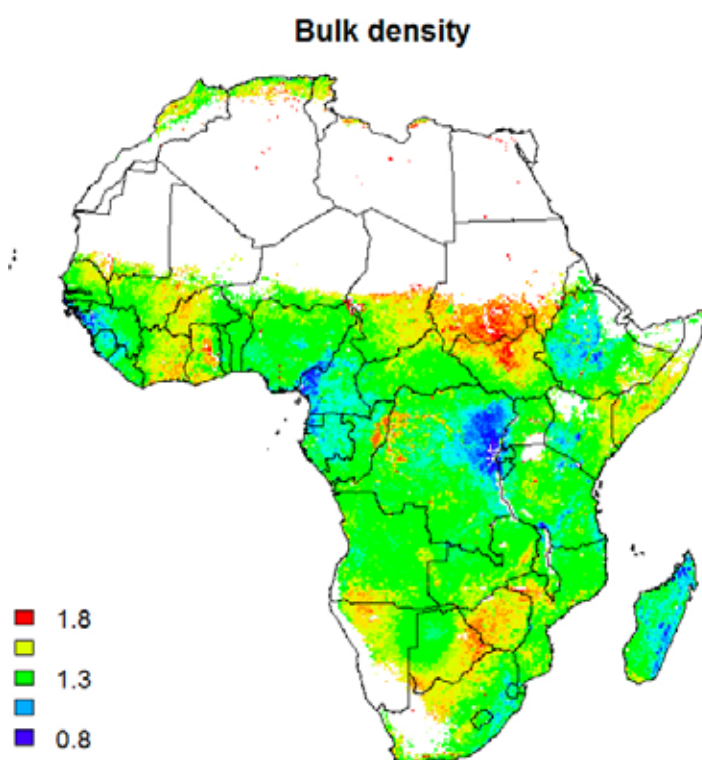


Figure-19a. Problems related to Soil bulk density.

SOIL COMPACTION

POOR ROOT GROWTH

WEAK MICROBIAL ACTIVITY

LOW POROSITY

REDUCED WATER INFILTRATION

INCREASED SOIL EROSION

POOR SOIL AERATION

POOR WATER MOVEMENT

WATER LOGGING

Biochar for soil health

Application of biochar to soils is known to improve the soil structure and soil fertility, apart from reducing run-off and erosion. Biochar has been reported to enhance cation exchange capacity (CEC) and enrich soil health by adding organic carbon (Venkatesh et al., 2013). Biochar produced from cotton stalks was found to contain about 1.1% nitrogen, 0.37% phosphorus and 0.1% potassium (Venkatesh et al., 2013). Biochar prepared from cotton stalks was found to have excellent cation exchange capacities in a range of 11.7 to 51.3 cmol/Kg (Venkatesh et al., 2013, Liang et al., 2006) and a high water-holding capacity of 3.9g/g due to its highly porous nature and a large surface area (Venkatesh et al., 2013, Xiang et al., 2017, Zhang et al., 2020). Thus, biochar has been reported to have positive impacts not only through carbon sequestration but also due to its immense potential for soil amendment and improvement of soil fertility. A global-scale meta-analysis of a dataset consisting of 184 pairwise observations for runoff and soil erosion from 30 independent studies showed that on an average, biochar application to soil reduced runoff by 25 % and erosion by 16%. Soil erosion in the tropics was reduced 3 times more than in the temperate zone (Gholamahmadi, et al., 2023). Application of biochar provides a safe habitat for fungi and bacteria due to its porosity that provides protection from predators and the water-holding capacity that protects microbes from desiccation (Hue, 2020; Zhang et al., 2010).

Table-3 Characteristics of biochar produced from cotton stalks at 350-400°C

Kg/Kiln	pH	CEC cmol/Kg	N g/Kg	P g/Kg	K g/Kgt	Carbon g/Kg
11	9.2	46.3	10.3	4.6	4.1	592.4
20	8.9	51.3	15.9	3.8	4.7	668.3
27	9.0	49.5	16.7	11.0	4.0	679.1

Source: Venkatesh et al., 2013

Enriching soil carbon

The UNCCD (2022) estimates that “up to 40 % of the planet’s land is degraded and threatens about half of global GDP worth US\$44 trillion”. Estimates showed that soil organic carbon SOC was displaced by soil water erosion to the tune of 2.5 Pg C yr⁻¹, of which thirty-six percent constituted agricultural land (Borrelli, et al., 2013). A significant issue in these soils is the low organic carbon content, which contributes to poor soil health. Unfortunately, there have been limited efforts to identify and implement long-term solutions to address these soil challenges in Africa. To promote sustainable agriculture and enhance agricultural productivity in the region, it is crucial to explore and implement strategies that address soil compaction, enhance organic carbon content, and foster overall soil health improvement. Conversion of biomass to biochar retains at least 50% of the initial carbon biomass (Lehmann et al., 2006) which when incorporated into the soil remains as recalcitrant carbon for hundreds and thousands of years, compared to a transient retention at much lower carbon sequestration rates due to slash and incorporation and almost a total loss of carbon that happens during the slash and char burning. Therefore, conversion of cotton stalks into biochar and incorporation into soil presents an excellent opportunity to create carbon rich soils that are stable over a long period of time.

Remediation of acidic soils

Biochar produced from cotton stalks is alkaline with a pH of >8.5 (Al Afif et al., 2015) with high values reported from 9.30 (Venkatesh et al., 2013) to 11.90 (Gao et al., 2021). Thus, biochar could be a boon to remediate acidic soils for resource-poor small holder farmers who cannot afford the expensive application of lime. Most soils in Africa are acidic and with high bulk density (meaning less porous and more compact). Unfortunately, acidic soils have low cation exchange capacity (CEC). Low CEC means that these soils do not retain nutrients such as potassium, calcium and magnesium that can be exchanged for hydrogen with roots. Soils deficient in these nutrients result in low yields. For acidic soils, addition of biochar produced from cotton stalks can be beneficial to neutralize and remediate the soil to a normal pH. However, a study also showed that the soil pH changed back to its original levels two years after applying biochar at 15 tons/ha, indicating that the pH-neutralizing effect of biochar could be transient (de la Rosa, et al., 2018) and repeated applications could be necessary for long term stabilization.

Biochar for non-acidic soils

The application of biochar produced from cotton stalks is restricted in alkali soil because of its high pH value (Zheng et al., 2019). Increased rates of biochar application under alkali soil conditions led to immobilization of nitrogen and micronutrients because of which yields of maize and wheat declined (Hussain et al., 2017). It has been found that the addition of organic matter and manure can further assist in enhancing soil health without the risk of ‘nutrient-lockup’ caused by biochar. Studies show that the best benefits from biochar application could be obtained when it was used along with organic manure or with materials that could alter the carbon: nitrogen ratio to 30:1. Organic manure and biochar significantly affected cotton root morphology and physiology and increased yields by improving soil nutrients (Xiang et al., 2017; Zhang et al., 2020). Composts produced through aerobic methods are slightly acidic in nature, but an anaerobic Japanese technique called Bokashi results in acidic compost (Higa and Pan 1994). Mixing Bokashi with biochar produced from cotton stalks can lead to a neutral pH, which would make the product suitable for all types of soils. A recent report showed that acid modification of biochar produced from cotton stalks was found to be eco-friendly, cheaper and effective choice in alleviating abiotic stresses from saline-sodic soil and positively effects maize and wheat productivity (El-Sharkawy et al., 2022).

THE CONE-PIT OPEN EARTH KILN TECHNIQUE

The characteristics of biochar and its biological activity can vary depending on the feedstock, pyrolysis temperature, and time the mass is heated (Blenis et al., 2023). The cone-pit open earth kiln technique combines anaerobic and aerobic pyrolysis and is an adaptation of the method described by Mr. Josiah Hunt in 2008.

Figure-20. Materials used in cone-pit open-earth kiln technique.



Materials

1. Dry stalks or branches: > 500 Kg
2. Crowbar to dig a pit and shovel to dig and excavate.
3. Match box to ignite.
4. Water drum, buckets/mugs/hose pipes etc.

Feedstock

Any organic biomass will be suitable for conversion into bio-mass. After harvest, one acre of a cotton field could have a crop-residue of 1.5-2.0 tons of cotton stalks. The left-over cotton stalks are either uprooted or cut above the ground level. If possible, the cotton stalks may be grouped into batches based on the thickness of the stalks.

Precaution: Cotton stalks are heaped at a place 2-3 meters away from the pit where it is proposed to prepare biochar.

Figure-21. Cotton stalks as feedstock



Conical pit

Dig a conical shape pit in the ground with dimensions of 2 meters in diameter and 1.5 meters deep. It is important that the pit should be in a 'V' shape and not in 'U' shape. Ensure that the pit is dry before you start the process of preparing biochar. Heap the dug-out soil near the pit.

Precaution: The circumference of the pit may be lined with stones and the border area rinsed with water immediately prior to the process to prevent any possible spread of fire.

Figure-22. Conical pit



Figure-23. Conical pit of 2.0 meters diameter and 1.5 meters depth



Chimney

Chop a few thicker stalks (>2.0cm thick) into 30-40 pieces that are about 30cm long. Arrange the stalks in a cross manner starting from the bottom of the pit to stack them in the central region as a cube that is about 30cm in length, 30cm in width and 45 to 60cm in height. Allow adequate aeration in the stack to minimize generation of smoke. Loosely arranged stacks and dry stalks generate less smoke. Ignite the chimney from the top leads to very less smoke compared to igniting from bottom which results in heavy smoke. Ignition will be quick with the use of a small amount of diesel or petrol, or kerosene poured over the upper pieces of stalks.

Figure-24. Preparing a chimney at the bottom of the pit and ignite it from the top.



First layer

Allow the chimney to burn to a point where the top layer starts showing a layer of ash around the stalks. At this stage, start adding the first layer of stalks slowly one by one towards the periphery of the pit next to the chimney.

The first few stalks that are added as bottom layers in the pit are preferred to be shorter (about 30-45cm long) and thicker (1.5-2.0cm thick). Ensure that the stalks are not thrown as packed bundles, which results in generation of smoke. Add stalks to fill about 15-20cm thick layer that covers the circumference of the lowermost part of the pit. Wait until this layer catches fire and spreads to the circumference.

Figure-25. The chimney on fire ignited from the top.



Figure-26. Adding the first layer of cotton stalks to cover the chimney.



Figure-27. First layer on fire.



Second layer

Allow the first layer to burn to a point where the uppermost stalks turn red with a layer of ash around them. At this stage, start adding the second layer of stalks slowly one by one towards the periphery of the pit first, followed by addition to the central region. Continue to throw stalks to ensure that the second layer gets to a thickness of about 20cm and covers the first layer completely, to prevent any entry of oxygen (air) into the lower layer to prevent it from burning more. As the second layer burns, you will notice that smoke gets significantly reduced.

Figure-28. Uppermost stalks of the first layer turn red with a layer of ash around them.



Figure-29. Adding the second layer of cotton stalks to cover the first layer.



Next layers

Allow the second layer to burn to a point where the uppermost stalks turn red with a layer of ash around them. At this stage, start adding the third layer of stalks slowly one by one towards the periphery of the pit first, followed by addition to the central region. Continue to throw stalks to ensure that the third layer gets to a thickness of about 20cm and covers the second layer completely all through the circumference, to prevent any entry of oxygen (air) into the lower layer to prevent it from burning more. Repeat this process of adding layers above the lower layers, to reach the uppermost region of the pit to fill it up.

Figure-30. Final layer on fire.



Quenching

Allow the topmost layer to burn to a point where the uppermost stalks turn red with a layer of ash around them. At this stage, squirt water or soil (if water is not available) on the fumes to douse the fire. Use adequate amount of water or soil to ensure that burning stops completely. Use of water results in bellows of white smoke, which is a combination of smoke, but mostly containing water vapor. Wait for some time for the contents to cool. Once cooled, carefully scoop out the biochar from the pit, taking care to avoid hot or smoldering material. Check to see if any pieces of stalks are still burning, to douse them immediately.

Figure-31. Quenching with water.



Figure-32. Scooping out biochar after cooling.



Pyrolysis

Biochar can be generated by incomplete combustion of biomass such as cotton stalks or any biowaste. Unlike aerobic pyrolysis which means burning in the presence of oxygen, anaerobic pyrolysis occurs at high temperatures in a controlled environment with limited or no oxygen supply.

The open-earth conical pit pyrolysis method described here uses the principles of aerobic and anaerobic pyrolysis to allow incomplete combustion of cotton stalks or any biomass through the following sequence of reactions:

1. Ignition of the chimney in the presence of oxygen (air) initially heats the stalks or wood, thereby leading to the release of vapor and pyrolytic gases such as methane (CH_4), carbon monoxide (CO), hydrogen (H_2), and volatile organic compounds (VOCs) from the stalks or wood.
2. The pyrolytic gases burn and spread the heat to the lower layers of stalks thus further leading to the release of more amount of the pyrolytic gases that catch fire and spread it all through the chimney pile.
3. The addition of layers of cotton stalks one above the other is done in a sequential manner so that the freshly added upper layer catches fire and burns in the presence of oxygen, which heats the stalks in the layer to release pyrolytic gases which burn thus generating more heat. This process of burning is allowed only to a point when the bark of the stalks in the upper layer is just about to turn into ash, but the inner part of the stem has released gases due the heat, but with most of the carbon still being intact. At this stage an additional layer of stalks is added above to work as a lid to restrict air flow into the lower layer and stop it from burning further, which leads to anaerobic pyrolysis of the lower layers.
4. The conical shape of the pit enables addition of layers of cotton stalks consequentially one above the other for each of the upper layers to completely cover the respective lower layers to prevent any entry of air into the lower layer to enable incomplete combustion through anaerobic pyrolysis of the lower layers.
5. Thus, the open-earth conical pit method produces biochar by using a combination of aerobic and anaerobic pyrolysis in sequential steps.

Fortifying biochar with compost

Soil organic carbon plays a crucial role in maintaining soil health, which is a significant challenge in agriculture worldwide. Enhancing the level of soil organic carbon in the topsoil is essential to revive soil health by promoting the populations of soil organisms and microorganisms. Biochar, as an inert carbon material, contributes to improving soil structure, increasing water holding capacity, and enhancing cation exchange capacity of the soil. It can be effectively utilized as part of an aerated matrix for composting by preparing a fertile biochar mix to boost soil fertility. Several commonly employed methods to enhance soil

health involve the use of biochar in conjunction with green manures, legume crops, and a biofertilizer extract called 'Jeevamrut' to facilitate composting. This can be achieved through aerated piles or closed containers for anaerobic composting using effective microorganisms (EM) in the Bokashi method.

Figure-33. Fortifying biochar with compost.



Aerated composting using biochar

Composting methods often rely on lime to counterbalance the acidic reactions that occur within the biomass during the fermentation process. However, biochar derived from cotton stalks presents a viable alternative as an alkaline source to replace lime. Biochar, in addition to its alkaline nature, offers the advantage of high porosity. This porosity enables biochar to serve as an excellent aerated matrix for aerobic fermentation. Consequently, the need for frequent turning of compost piles during fermentation can be eliminated. By utilizing biochar as an alkaline component in composting, not only can we effectively neutralize acidity, but we can also enhance aeration within the composting process. This streamlined approach simplifies composting procedures while maintaining optimal conditions for decomposition and nutrient cycling.

Organic matter contains valuable nutrients, but for these nutrients to become readily available to plants, they need to be decomposed by microorganisms through composting methods. Composting is a process where soil microorganisms break down organic matter to produce compost, which can greatly enhance soil health. Organic matter harbors various microorganisms, such as bacteria, actinomycetes, and fungi, which feed on and decompose the organic material. These microorganisms require oxygen, water, air, warmth, carbon, nitrogen, and other minerals for their survival and activity. The effectiveness of composting relies on factors such as the population and composition of different microorganisms, the carbon-to-nitrogen ratio (ideally around 30:1) in the feedstock material, appropriate oxygen levels (around 5%), suitable moisture levels (between 40-60%), temperature within the range of 40-60°C, the physical structure of the material being composted, and a pH range of 6-8. Microorganisms efficiently break down organic matter during composting, resulting in the production of compost, which is a dark brown, humus-like material that serves as an excellent soil conditioner. Compost enriches the soil by enhancing its nutrient

content, improving soil structure, and promoting beneficial microbial activity, ultimately contributing to the overall health and fertility of the soil.

Figure-34. Preparing aerated composting bed using biochar as matrix.



To create an aerated bed for composting, a fertile biochar mix can be prepared by combining the following components: Two tons of crushed biochar, eight tons of compost/manure, 200-500 kg of dry hay, and two tons of green manure leaves. These components should be thoroughly mixed with topsoil to form a raised flatbed measuring 15-20 cm in height. Additionally, 50 liters of Jeevamrut, a biofertilizer extract, should be added to the mix. Legume seeds, such as cowpea or mung beans, should be broadcasted onto the raised bed, and a mulch of biochar or dry grass can be applied. Allowing the crop to grow until flowering, the legume crop should then be incorporated into the topsoil. Finally, the prepared mixture can be utilized to create rows or ridges in the fields for planting cotton seeds, thereby promoting soil health and supporting successful crop cultivation.

Jeevamrut

Jeevamrut is a valuable solution rich in soil microorganisms and is commonly used as an inoculant for compost preparation and soil enrichment. To prepare a jeevamrut solution, mix 500 ml of cow urine with 20 liters of water. Add 2 kg of cow dung, 1 kg of forest soil, 200 grams of jaggery, and 200 grams of legume seed powder to the solution. Allow the mixture to ferment for 3 to 4 days. This solution can be sprinkled on a composting heap or filtered, diluted five times with water, and sprayed in a one-acre field as frequently as possible. Jeevamrut helps to promote beneficial microbial activity and nutrient cycling in the soil (Rathore et al., 2023).

Bokashi

The Bokashi method involves fermenting organic matter to produce a nutrient-rich biofertilizer. Bokashi can be prepared in near-airtight bins using a consortium of effective microorganisms (EM), including photosynthetic bacteria, species of *Rho-*

dopseudomonas, lactic acid bacteria, species of *Lactobacillus*, and yeasts like *Saccharomyces*. For a liquid preparation, mix 50 ml of EM with 4 kg of cow dung, 4 kg of biowaste, 4 kg of compost, 200 grams of bran, 10 grams of lime, 20 grams of yeast, 20 grams of sugarcane molasses, and 2.25 liters of water. Biochar can be added during fermentation or after fermentation to the compost, with a total volume equal to the biomass, to neutralize any acidity. Ferment the mixture for one to two weeks to obtain high-quality Bokashi compost, which can then be diluted and used for fertilization purposes. The addition of biochar helps stabilize the acidic fermenting mixture or compost and enhances its effectiveness.

Figure-35. Preparing Jeevamrut to inoculate compost beds.



Figure-36. Preparing Bokashi compost.



Biochar in vermicomposting

Biochar can be utilized to enhance the vermicomposting process, which involves the use of earthworms to convert organic waste into nutrient-rich compost. Experiments with northern hemisphere composting worms, specifically *Eisenia fetida*, have demonstrated successful biochar-based vermicomposting (Malinska et al., 2017). For instance, the addition of 8% biochar to wood feed based in sewage sludge resulted in a remarkable 66% increase in cocoon production (Malinska et al., 2016). In vermicomposting, the use of earthworms helps in breaking down farm waste and cattle manure into compost. To prevent the earthworms from escaping into the soil, cement or polythene layered pits are created. The necessary materials for compost-

ing include biochar, biological waste, manure, lime or gypsum (in the absence of biochar), water, and earthworms.

Figure-37. Vermicompost prepared using biochar.



Application to soil

The ICAC has developed techniques to fortify biochar with compost, aiming to achieve a near-ideal carbon-to-nitrogen ratio of 30:1, as outlined by Kammann et al. (2016). Our experience has demonstrated that it is feasible to convert 2-3 tons of cotton stalks into biochar within a day using the cone-pit open earth kiln technique.

Figure-38. Soil incorporation of fortified biochar as band application in rows.



The production process, including biochar, bokashi, and the mixing of the two to fortify biochar with microorganisms and nutrients, generally takes approximately 3-4 weeks. To obtain fortified biochar, typically, one ton of biochar is mixed with 2 tons of compost, resulting in a yield of 3 tons of fortified biochar. The fortified biochar can be applied directly on the soil surface as a top dressing or incorporated into the soil through tillage. It is advantageous to coordinate the application with key growth stages of the crops to maximize nutrient availability and uptake. Soil moisture conditions should also be taken into consideration during application. Applying the fortified biochar when the soil is adequately moist, without being excessively wet, allows for better incorporation and nutrient release.

For field application, the ideal recommended rate is approximately 6 tons of fortified biochar per acre, though lesser volumes can be used, preferably in rows where cotton seeds are sown. A strategic approach involves applying fortified biochar to one row in each season and repeating the process in an adjacent row the following season. This rotation ensures that the entire field will be covered with a layer of fortified biochar within 3-4 years. Alternatively, a method involving layering one-fourth of an acre with 6 tons of fortified biochar each year can be employed, achieving full coverage of the acre within 4 years.

It is worth noting that complete coverage of the field with fortified biochar has shown weed-suppressing properties, enabling the initiation of conservation tillage practices without the need for chemical herbicides. By implementing this approach, farmers can gradually transition to no-till techniques combined with more sustainable and environmentally friendly weed management methods.

Over the past two years, the ICAC has actively conducted several practical training programs to popularize the 'cone-pit open earth kiln' method. Starting with initial training sessions in Zambia, Cameroon, Burkina Faso, and other countries, the technique has gained significant traction and adoption. Currently, hundreds of farmers across Africa have embraced this method, and its momentum continues to grow. Notably, the technique is being taught and promoted in Bangladesh by Cotton Connect, in Zambia by Cotton Development Trust (CDT) and Solidaridad, in Côte d'Ivoire by Olam Agri and Ivoire Coton, in Cameroon by Sodecoton, and in India by multiple organizations. This widespread implementation showcases the method's effectiveness and its positive impact on agricultural practices in various regions.

Conclusion

The cone-pit open earth kiln technique is not only practical and simple but is also inexpensive and an effective method in producing excellent quality biochar from cotton stalks and similar woody material. Though there is evidence that ancient farmers used it widely in many parts of the world, in recent times, thus far, biochar has not been used mostly in experiments but not on a mass scale in agriculture. One of the reasons for low adaptability is the prohibitive cost of production. The cost of producing one tonne of biochar using an orchard system's waste and a mobile pyrolysis unit in California was around \$450-\$1850 (Nem-

atian et al., 2021) and \$600 to \$1300 (Thengane et al., 2021). The cone-pit open earth kiln technique costs almost nothing, except labour work that involves manual work such as, digging a pit, regulating pyrolysis of cotton stalks, quenching, scooping and application in the field. Interestingly, it is now possible that farmers will be rewarded through payments in the range of \$193 to \$234 per ton (Blenis et al., 2023) on carbon credits for improving their soil health. Most soils in Africa are acidic and with high bulk density meaning less porous and more compact. Unfortunately, acidic soils have low cation exchange capacity or CEC which leads to deficiency of potassium, calcium and magnesium that results in low yields. The cone-pit open earth kiln technology is powerful in remedying acidic soils, yet so simple to operate that it can easily emerge as a game changer for small holder farmers in Africa to improve soil health and thereby increase yields, especially where soils are acidic.

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