Heliyon 9 (2023) e15896

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

The *Terra Preta Model* soil for sustainable sedentary yam production in West Africa

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ARTICLE INFO

Keywords:
Amazonian dark earth
Biochar
Ecological sanitation
Soil degradation
Agro-industry waste
Waste charcoal

ABSTRACT

Current declines in yam yields amidst increasing cultivated areas, land scarcity, and population surges call for more sustainable sedentary yam production systems. This study explored the nature of Amazonian Dark Earths (ADEs) as a basis for the formation of a related soil type known as the *Terra Preta Model* (TPM) soil for future sedentary yam systems. It builds on the influence of human beings in soil management and the formation of Anthrosols. Previous studies on the ADEs and biochar were synthesized to establish the fundamental assumptions required to form the TPM soil. The practical approach to forming the TPM soils is based on the intentional, integrated and prolonged use of biochar, municipal solid wastes, agro-industry wastes and products of ecological sanitation. Tillage options such as mounding, ridging, trenching and sack farming could be used for yam production on the TPM soils. Unlike natural soils, the longevity of ADE fertility is subject to debate depending on crops grown and cropping cycles. Therefore, a crop rotation plan is recommended to maintain the fertility of the TPM soils. The TPM soils, if adopted, are considered worthwhile for the long-term benefit of biodiversity conservation, efficient waste management, enhanced ecosystem services provided by soils and extensive adoption of ecological sanitation.

1. Introduction

Yam (*Dioscorea* spp) production has increased from 14.5 million metric tons to 66.8 million tons within three decades (1988–2018) at an annual rate of about 3.8% from 2000 to 2019 [1]. This drastic increase in yam production was attributed to expansion in the area under cultivation, which occurred in the Savanna and Forest-Savanna Transition agro-ecological zones of West Africa. Incidentally, these zones had a traditional fallow period of 20 years but is now decreased to less than five years with associated declines in yam yields due to soil degradation. In a previous review on the ecological and edaphic drivers of yam production in West Africa, edaphic drivers were the main determinants of yam yields [2]. This has been the fundamental reason for the preponderance of shifting cultivation and fallow systems in the yam belt of West Africa where yam is often the first crop on freshly cleared native vegetation or fallows. In soils of freshly cleared land (forest or fallow), the biological, chemical and physical properties of the soils are suitable for *in situ* yam tuber expansion. This benefit only lasts for one or two yam cropping seasons because of the heavy-feeding nature of yam. The heavy-feeding habit of yam necessitates the quest for the next piece of “virgin” land. Consequently, current population trends, the huge

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Abbreviations: ADE, TPM; SOC, CEC; MSW, WHC.

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https://doi.org/10.1016/j.heliyon.2023.e15896
Received 27 August 2022; Received in revised form 21 February 2023; Accepted 25 April 2023

demands for land, and the prevalent nutrient-mining nature of agricultural systems in Sub-Saharan Africa [3,4] call for sedentary yam production systems. Sedentary yam farming systems require strategies that can provide the soil quality similar to that of virgin lands to close the existing yam yield gaps.

Research on yam production promoted the application of chemical fertilizers in the past. This increased yam yields but many West African farmers still cultivate yam without fertilizers. Culturally and traditionally, it is convenient to depend on the native soil fertility and thus practice shifting cultivation [5,6] in areas with abundant native vegetation land space. This practice has implications for the achievement of the sustainable development goals and climate actions. Attempts to employ chemical fertilizers to improve yam yields [7–9] tend to cause gradual yield decline in subsequent years as in the case of freshly cleared lands [10–12]. Also, the deteriorative effects of chemical fertilizers on some soil properties are well known. These include acidification, effects on soil ecology, no effects on physical properties of soil and possible losses by leaching, volatilization and surface run-off [13,14] and negative priming effect in soil [15,16]. Hgaza et al. [17] observed an increase in yam tuber yield when NPK fertilizer was applied to nutrient-depleted Savanna soils. However, since the authors used ^{15}N labeled stable isotope as an N source, they could prove that, the applied fertilizer caused an increase in the yam uptake of N derived from the native soil. They, therefore, concluded that the added fertilizer stimulated rapid mineralization of SOM which increased the crop uptake of N derived from the soil to increase yield. This negative priming effect caused by the chemical fertilizer can be detrimental to soils with low organic matter content [6]. More importantly, chemical fertilizers affect the organoleptic properties of yam tubers [18–20] and other root crops [21].

In contrast, sole and combined applications of organic and chemical fertilizers increased yam tuber yields [19]. Sole applications of organic fertilizers increased yam yields by 7–20% as well as the starch, crude protein, K, Ca and Mg and lower oxalate contents [19,22]. The sole application of chemical fertilizers may not offer the best solution for sustainable yam production. An integrated approach to organic chemical fertilizers may be the best way to improve soil properties as seen in a previous review [2]. This approach improved yam yields in many soil types and locations, particularly from the second year of continuous application [19,20,22]. Sadly, the warm temperatures of West Africa do not proffer a sustainable solution due to fast SOM decomposition rates [23]. This is the challenge in an ever-changing climate and a research gap that needs immediate attention.

As a first step to filling this gap, the adoption of practices that mimic the formation of the highly productive Amazonian dark earths (ADEs) could help to stabilize or slow down SOM decomposition and enhance crop yields per unit area. Consequently, the *Terra Preta Model* soil was proposed earlier by Neina [2]. This implies that every approach or technique that enhances the formation of ADEs could be adopted to curb soil degradation linked to yam production [24,25]. Since yam production is still below its potential [26] due to edaphic constraints [2], it is imperative to find a more sustainable approach to eliminating these constraints. In a case study on the transformation of traditional shifting cultivation into sedentary systems in Ecuador, Schritt et al. [27] assessed household nutrient input and output and concluded that ecological sanitation and the application of ADEs principle could create sedentary farming systems. Arroyo-Kalin [28] states that the formation of ADEs represents a positive feedback loop between sedentariness and soil fertility. Previously, Glaser [24] advocated the generation of the Amazonian dark earth (ADE) to establish "highly productive and sustainable land use systems" and long-term sequestration of C by adopting well-thought-out material management [25]. Further, Alho et al. [29] emphasized that studies on the ADEs affords the insights required for future sustainable agricultural practices in the tropics, while Asare [30] suggested that the adoption of ADEs development process in arable lands has sustainable prospects for the future of agriculture. Although the ADEs have been widely examined and studied under different disciplines to decipher the origin, history and properties [30–37], the specific processes that led to their formation is still under contention. This has created a bottleneck in the effective replication of ADEs in other places to generate a new research discourse. Rather, research has been heavily focused on the wide use of biochar whose benefits have been heavily proclaimed without considering potential adverse effects [38–41]. The huge amount of research committed to biochar seems to be a slow disconnection of biochar from the ADEs [42]. Consequently, many of the observed adverse effects of biochar application [38,39,41] are caused by some avoidable factors that have been enumerated here including: (a) Choice of biochar and soil types, their actual interactions and the target soil properties; (b) Mode of biochar application – light biochar applied solely under windy environments are likely to promote erosion; (c) Sole biochar applications under controlled environments that excludes plants and the influence of rainfall; and (d) Crop and soil type, the influence of the external climate environment.

The goal of this paper is not to conduct a review or meta-analysis of biochar applications per se, but is rather to examine the nature, formation, composition and properties of the ADEs as a foundation to guide in the *Terra Preta Model* soil formation as proposed earlier by Neina [2], the concept of the *Terra Preta Model* (TPM) soil, materials and techniques required for the formation of the *Terra Preta Model* soil, propose management practices to sustain its productivity, and suggestions for future research direction. Eventually, the content of this paper may invoke more thoughts and strategies in designing specific soil conditions to obtain specific food quality from crops. In other words, "designing" soils for "designer crops". Although the proposed TPM soil targets yam production in West Africa, it is equally applicable to the cultivation of other crops.

2. The approach

The approach to describing the TPM soil involved the search for published data in Google Scholar, ScienceDirect, Wiley, Taylor and Francis, and Springer with no limit to any date of publication. The search involved four stages:

Stage 1: This stage was used to establish the origin, development, nature and use of ADEs. We used key words such as "Terra preta", "Amazonian dark earth", "ADE", together with related key words like "development", "composition", "properties", "crop yields", "yields", "char", "charcoal".

Stage 2: This was find out if any artificial ADEs have been proposed and are being studied or utilized. Key search words were: "Terra

Preta Model soil", "mimicking the Amazonian dark earth", "applications of Amazonian dark earth", "creating new terra preta soils".

Stage 3: This stage focused on the black carbon in ADEs which has received so much research attention. The search words were: "char", "charcoal", "biochar" along with "soil properties", "crop yields", "manure", "composts", "co-application", "co-compost", "pyrolysis", "saw dust", "rice", "kitchen wastes", fertilizer, "hazards", "risks", "adverse effects", "yam", "yam production" and "Dioscorea production".

Stage 4: This stage was used to assess literature decomposable wastes such as "human excreta", "urine", "human urine fertilizer", "fecal matter", "ecological sanitation", "wood ash", "ash", "kitchen wastes", "animal manure", "wastes from agro-processing", "livestock and manure in West Africa".

3. Concept of the terra preta model soil

The TPM soil has been conceptualized in the scheme presented in Fig. 1 which comprises the foundation built on the ADEs and the TPM itself as a "house" under the influence of a "roof" of influencing factors that aid in its formation.

3.1. *Origin and properties of the Amazonian Dark Earths*

As stated earlier, the concept of the TPM soil (bottom of Fig. 1) is based on the original Terra preta or ADEs. The original terra preta are typically dark soils of central Amazonia known as the Amazonian Dark Earths (ADEs), Anthropogenic Dark Earths [25] or Indian Black Earth [34]. The local residents generally do not know how these soils came about. While some viewed the ADEs to be of natural origin, others believe that they are human artifacts [33]. Nonetheless, the ADEs are now considered to be anthropic (unintentionally formed) or anthropogenic (intentionally formed) [30,43]. Previous studies suggest that the ADEs formed from biogeochemical transformations of a mixture of domestic wastes such as kitchen wastes (including ash mixed with charcoal fragments), faecal matter, animal manure and charcoal dumped over time [24,44]. The whole process was influenced by (a) a high population density at the time, (b) persistent deposition of materials [30,31,43], and (perhaps intermittently or alternating cycles) as part of their livelihood strategies. Consequently, ADEs are Oxisols, Ultisols and Inceptisols enriched with a thick dark carbon-rich anthropic A horizon [34,36,45]. The ADEs, therefore, consist of original soil, organic matter and black carbon. This process is similar to the development of "dump site soils" (soils of refuse dump sites) where open dumping of refuse dominated by decomposable materials usually takes place.

The A horizon is formed by melanization as soil fauna thoroughly mix up substantial amounts of ash, charcoal and organic matter added to the soil (Glaser 2003, cited by Arroyo-Kalin [28]. The ADE horizon has a crumb structure with very stable aggregates [34], slightly higher pH (usually less acidic), two to three-fold the CEC of adjacent soils [25,46], high base saturation and available P content [34,46] as well as high amounts of both labile and recalcitrant soil organic carbon (SOC) than adjacent soils [47]. The SOC breaks down continuously to release nutrients to plants depicting slow-release fertilization [25]. The ADEs are biologically enriched with an abundance of earthworms [34] and has about 25% high bacteria species richness [37,48,49]. The SOM is, however, more stable [24] and has about 70 times more charcoal than adjacent soils [24,36]. The dark colour of the soils and the substantial amount of charcoal present in ADE stimulated interest leading to the conclusion that charcoal possesses essential properties for soil conditioning. The ADEs are endowed with about twice the fertility (Table 1) and crop productivity of adjacent soils within the same environment [24]. This has been confirmed by both farmers [36] and researchers [24,32]. The superior fertility and productivity of ADEs have been attributed to human interventions through the addition of plant and animal residues, ash, charcoal, organic manure, faecal matter accumulation leading to the formation of the soils [24,46]. The formation and composition of the ADEs could be then used as the foundation of the TPM soil as illustrated in Fig. 1.

3.2. *The terra preta model soil*

The TPM soil is an anthropogenic soil that possesses properties similar to those of ADEs ("house" of Fig. 1), and is produced through

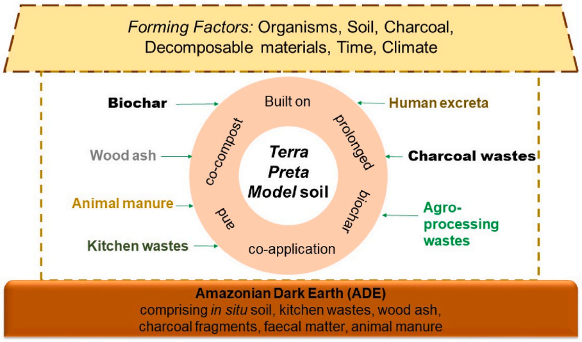

Fig. 1. The concept of the Terre Preta Model soil built on the ADEs as the foundation. It is composed of materials as in the case of the ADEs and its formation is conditioned by the influence of factors similar to those of soil formation.

Table 1
Properties of the ADE that are suitable for yam production.

Soil type	Horizon depth (cm)	Bulk density (g cm^{-3})	Soil pH	C	N	Total P	CEC	BS
				g kg-1			($mmol_c$ kg^{-1})	(%)
Terra Preta*	0–40	–	5.2	33.5	2.2	–	123.0	87.5
Oxisol*	0–40	–	4.2	13.9	1.0	–	13.0	5.5
Terra Preta*	–	–	4.9	31.5	1.8	5.0	222.4	–
Adjacent soil*	–	–	3.5	17.5	1.3	0.3	59.2	–
Terra Preta 1	0–20	1.05	4.7	23.0	2.6	0.94	–	–
Adjacent soil	0–20	1.20	4.5	17.5	1.9	0.21	–	–
Terra Preta 2	0–30	–	6.2	–	–	1.99	–	71.0
Adjacent soil	0–18	–	4.6	–	–	0.001	–	50.0
Terra Preta 2*	0–40	–	5.4	32.7	2.2	$0.143^{¥}$	$129.5^{\#}$	96.5
Adjacent soil*	0–40	–	4.0	11.5	0.9	$0.003^{¥}$	$47.0^{\#}$	4.5

Data sources: Glaser et al. [45]; O'Neill et al. [37]; Orozco-Ortiz et al. [137]; Lima et al. [34]; Birk et al. [96]. *(0–40 cm) in pH KCl; Most authors did not include standard deviations, $^{\#}$effective CEC, $^{¥}$available P.

repeated and long-term applications of biochar co-applications (with organic matter), biochar co-compost and possibly off-site soil-biochar-organic matter co-compost. Since the formation of the ADEs is influenced by population density and persistent deposition of materials (decomposable and virtually persistent) on the soil surface as stated earlier, it is concluded that the TPM soil could also be designed and established. The setting of the ADEs denotes availability of a large volume of materials and frequency of deposition. Among the factors of soil formation and pedogenesis, the role of organisms is strongly recognized. Human beings are equally important as they play a major role in pedogenesis. This role has been manifested in the formation of the ADEs [25,34] and other Anthrosols [50] leading to unique impacts on soil properties. Often, the impacts have been negative leading to soil degradation of various types and degrees. Now is the time to effortlessly work towards achieving more positive than negative human impacts through conscious actions. The physical and chemical properties of ADEs can be likened to those of dump site soils which consist of a mix of ashes, charcoal and various forms of decomposable organic materials. However, dump site soils contain substantial amounts of toxic trace elements mostly from inorganic wastes [51]. Meanwhile, the time required to develop ADE is unknown although some climate variables could make a difference [25]. For instance, in the arid zone of Saudi Arabia, Waqas et al. [52] achieved the stability of biochar co-compost comprising 15% (w/w) of biochar added to food wastes within 50–60 days.

Unlike the ADEs which may or may not have been consciously developed [25], the TPM soil is one that can be designed and consciously developed for a specific purpose by combining selected materials for the purpose. The model soil may have a long-term and additive impact of overcoming not only soil degradation but also water stress in arid areas [53] due to its ability to enhance the water holding capacity (WHC) of soils [54]. Since ADEs are a product of human interventions involving the intentional and unintentional addition of materials, it can be concluded that its formation, and for that matter, TPM soil is influenced by the action of organisms, existing soil, charcoal, decomposable organic materials produced with time under the influence of varied climatic conditions. Therefore, the function is similar to regular soil formation and can be described by equation (1). It is assumed that the final properties of TPM will depend on the native soil properties, biochar type, the quality of decomposable materials and climatic conditions under which it is formed.

$$TPM = f\,(Organisms,\ Soil,\ Charcoal,\ Decomposable\ materials,\ Time,\ Climate) \tag{1}$$

3.3. Proposed composition

Most of the adverse effects of biochar use could be avoided if the biochar-soil-crop interactions, nutrient requirements, and ecological conditions were given careful considerations. It is also important to consider if such adverse effects of charcoal have been observed in the ADEs. In other words, reconnecting biochar to the ADEs. Based on the scheme presented Fig. 1, the TPM soil comprises:

3.3.1. Black carbon

3.3.1.1. Waste charcoal. The quantity of black carbon occurring as charcoal amounted to about 35% [45]. Besides, its alkali content enhanced the pH, CEC and base saturation of the native soils [45]. The original black carbon in the ADEs was mostly described as charcoal [30,43,45,55], which persists in soils compared to normal SOM and has a residence time of less than four years [56]. Considering the nature of the peoples livelihoods, it is clear the black carbon was charred biomass produced under natural or traditional charcoal burning conditions compared to the current biochar produced from different feedstock of both plant and animal origin and under controlled conditions. Charcoal can still be used for the TPM soil as a waste generation during production and transport, although this recommendation does not promote charcoal production and deforestation. The point here is that charcoal consumption in West Africa is substantial due to high costs of other fuel sources for domestic uses. Its production occurs in remote rural areas where it is distributed by road transport. Often, prolonged transportation exposes the charcoal to breaking into particle sizes. About 5–10% of the charcoal is hauled to urban areas and depots break into more powdery forms beyond sizes suitable for use in coal pots and lose their calorific value. This charcoal fraction, waste charcoal, becomes waste after sales and could be harnessed for the TPM soil. It could also be counted as Municipal Solid Waste (MSW) and harnessed for use. Waste charcoal is said to be very useful for soil fertility improvement, particularly at kiln sites. For instance, Oguntunde et al. [57] observed an 88% increase in the saturated hydraulic conductivity, a 9% reduction in bulk density and a 50.6% increase in total porosity of kiln site soils (Haplic Acrisols) in the Forest-Savannah Transition zone of Ghana. Further, Coomes and Miltner [58] estimated that kilns incorporate about 30 metric tons of waste charcoal per year into the Ultisols of the Peruvian Amazon. They also discovered that soils of charcoal kiln sites had significantly higher total N and P contents, base saturation, effective CEC, soil pH and reduced bulk density compared to non-kiln sites. In another study of ADEs and nineteenth century sites of charcoal kiln activities, the soils of the charcoal kiln sites exhibited high CEC yielding fertile soils. More so, there was a high were structural similarity between the humic acids of the paleo-charcoal kilns soils and those of ADEs which suggested the same development processes [55]. Although the regular charcoal is produced mostly from hardwood and under temperatures lower 350 and 470 °C) [58,59], than those of biochar are known to have properties that may be suitable as a soil conditioner (Table 2), and consequently for the TPM soil. Sadly, there is still inadequate research on the benefits and adverse effects of this type of charcoal compared intentionally prepared biochar.

3.3.1.2. Biochar. The presence of charcoal motivated the wide use of biochar as a soil conditioner. The feedstock types used vary widely with different compositions of molecular constituents such as cellulose, hemicellulose, and lignin [60]. For sustainability, it is imperative to differentiate between feedstocks that have 'competitive on-farm uses' and those 'without competitive on-farm use' to in order to choose the best feedstocks for exclusive use for biochar. The feedstocks with 'competitive on-farm uses' here refers to substrates that can be conveniently incorporated directly into the soil in the field, or be included as a source of decomposable materials for the TPM. Examples of such feedstocks include crop residues, animal manure (those that contain less hazardous components), wood wastes, varied agro-processing industry wastes, municipal solid wastes, and kitchen wastes (Table 3). Therefore, decomposable organic wastes that can conveniently be incorporated into the soils should be discouraged, particularly those that are less carbonaceous. Additionally, feedstocks that produce highly alkaline biochar [54], have low contents of toxic trace elements, animal manures heavily loaded with antibiotics, growth hormones and pyrolysis temperatures that enhance CEC [61] should be considered. Another factor is the availability and accessibility of the feedstock, which varies from place to place [62,63].

Biochar production should consider pyrolysis temperatures that produce biochar properties suitable for the TPM soil. Biochar obtained by slow pyrolysis, which is similar to traditional charcoal production (replicable maximum temperature between 350 and 470 °C) [58,59], are known to have properties that may be suitable as a soil conditioner (Table 2), and consequently for the TPM soil. For instance, the low biochar bulk density reduces soil bulk density by diluting it [62,64] depending on the rate of application [65,66] and the particle size [65]. Biochar with high alkalinity (pH and basic cation contents) are produced at higher temperatures (>500 °C) [67,68], while lower temperatures (i.e. those of traditional charcoal kilns) produce higher biochar CEC [67,68]. Even at the same temperature, the feedstock type also affects the CEC obtained as manure-based feedstock, sludge, sawdust, wood and rice husk biochar produce high CEC biochar [54,61,62,67,68]. Biochar also contains some N and substantial amounts of basic cations [61], resulting from the total alkalinity of biochar [69]. Consequently, Sadaf et al. [70] differentiate between nutrient and structural biochar where the former improves soil fertility and crop yields, whereas the latter improves soil structural properties. However, since these two edaphic factors are equally essential for good yam yields, the effects of both nutrient and structural biochar could be explored vis-à-vis organic and mineral fertilizers.

Biochar application has not only increased crop yields [15,61,71–73] but has had integrated effects on the biological [74–76], chemical [77,78] and physical properties of the soil [79–82]. Biochar has a bulk density range of 0.14–0.24 g cm^{-3} [62] and tends to dilute the bulk density of soils. In a review, Blanco-Canqui [64] observed that biochar application reduced bulk density by 12% with greater effects in coarse-textured soils (14.2%) than in fine-textured soils (9.2%). Similarly, Ghorbani et al. [79] found stronger effects of biochar on the bulk density of loamy sand (1.61–1.26 g cm^{-3}) than clayey soils (1.31–1.21 g cm^{-3}) with an application rate of 3%

Table 2
Selected chemical properties of biochar required for the Terra Preta Model.

Biochar type	Pyrolysis Temperature	pH	Ca	K	Mg	P	C	N	CEC
	(°C)		(mg kg^{-1})				(%)		(cmol kg^{-1})
Rice husk	300–350	8.0	220	175	182	–	43.7	1.0	–
Wood biochar	250–300	7.3	273	305	72.2	–	52.7	0.72	–
Wood biochar®	360–470	9.2	330.7	463.8	48.9	29.8	72.9	0.76	11.2
	350–450								
Saw dust	300	7.9	–	–	–	–	58.2	0.52	–
Rice husk	300	7.6	–	–	–	–	49.3	2.13	–
Saw dust	350	5.8	–	–	–	–	52.3	0.15	56.1
	450	6.3	–	–	–	–	58.2	0.16	52.4
Rice husk	350	6.4	–	–	–	–	44.3	0.78	41.4
	450	6.9	–	–	–	–	46.6	0.85	36.2
Poultry litter*	350	6.3	–	–	–	–	25.3	0.22	67.2
	450	9.5	–	–	–	–	27.0	0.25	53.5

Data sources: Varela et al. [54]; Major et al. [61]; Schulz et al. [59]; Fatima et al. [138]; Pariyar et al. [68]. *Recommended for those containing a lot of antibiotic; ®Temperatures for traditional mound kiln.

Table 3
Biochar feedstocks available in West Africa.

Non-competitive on-farm use	Competitive on-farm use
Corn cobs*, cassava stalks/residues, rice husk from mills, coffee husk, peanut hull/husk, saw dust, wood shavings, cocoa wastes (pod, husk), coconut wastes (shell, husk), sugar cane bagasse, oil palm wastes (fruit bunch, fibre, kernel shell), fecal matter#, Animal manure enriched with hormones and antibiotics	Maize, rice, millet, sorghum straw and stalks, animal manure free from hormones and antibiotics

*May have competitive uses in places with limited sources of firewood. #For the elimination of pathogens.

(w/w) beyond rates recommended by Verheijen et al. [83]. These suggest that biochar application could create the required condition for healthy yam tuber expansion. Furthermore, the low biochar bulk density also translates into high porosity and WHC depending on the feedstock and the native soil texture. For instance, rice husk biochar had 1.5 more WHC than wood [54]. Biochar application increased the WHC of sandy soil, slightly increased it in the loam but reduced it in the clayey soil [84]. Yam is grown mostly in the Savannah and Forest-Savannah transition zones of West Africa where the pH of the soil is slightly acidic to almost neutral [85,86] except under continuous cultivation and the intensive use of mineral nitrogen fertilizers. Therefore, biochar types and application rates employed should consider native soil pH and its response to biochar application to avoid the detrimental effects of higher rates.

3.3.2. Decomposable materials

3.3.2.1. Decomposable municipal solid and agro-industry wastes. Municipal solid wastes (MSW) consist of refuse from households, markets, yard weeding, mowing and trimmings or pruning, and street sweeping, which may be in solid or liquid forms [87]. The decomposable fraction of MSW ranges from 48 to 69%, depending on the origin (e.g. districts, municipalities and metropolis) [88]. This is because the amount and composition of wastes generated depend on demographics, the standard of living, culture, type of settlement and geographical location [88,89]. Organic components of MSW from homes and marketplaces are a major source of biodegradable waste (<60% for Ghana) [88]. Sadly, this fraction has been underutilized due to infrastructural challenges. Yet, it can be effectively harnessed if well sorted at source. As the most urbanized region in sub-Saharan Africa with about 50% of the population living in urban areas as of 2013 [90], plans must be put in place in West Africa to turn these wastes into valuable resources. Another source of decomposable waste for the TPM soil is waste from agro-processing industries. Agro-processing involves the transformation of raw agricultural products taken through primary, secondary, or tertiary processes. In a report of agricultural growth in West Africa, Hollinger and Staatz [90], observed that although agro-processing takes place in the region, there are intensive formal-sector firms in Nigeria, Côte d'Ivoire and Ghana, which are also the big players in yam production. The major agro-industries focuses on semi-industrial processing of oil crops, cereals, roots and tubers, fruit juice and tomato processing [90]. Most of these crops are processed into value-added products leaving enormous non-carbonaceous wastes to be disposed of. The wastes can be categorized as those with competitive and non-competitive uses.

3.3.2.2. Animal manure. The livestock industry is rapidly growing to meet the ever-increasing global population protein demand. Thus, large quantities of animal manure are being generated. It is been estimated that more than fifty-five (55) billion metric tons of manure are produced annually worldwide, of which 18.5 billion are from cattle, 34 billion from poultry, 1.5 billion from pigs and 0.8 billion from sheep [91]. This manure contains essential nutrients (Table 4) which can be harnessed for crop production. In West Africa, livestock plays an important role in agricultural systems and has the strongest market growth potential for animal products [90]. In addition to the value of livestock labour and manure, the West African livestock sector contributes to about 50% of agricultural gross domestic product [92]. Moreover, the role of the mixed agriculture-livestock production systems of West Africa in soil quality improvement and environmental management [92] cannot be underestimated. The vast livestock of West Africa include ruminants such as cattle, goats, sheep, donkeys, camels, horses, monogastric livestock such as poultry (ducks, fowls, guinea fowls, turkeys, and ostrich), pigs, rabbits, hares, among others. The existing rearing systems could be improved to harness manure for use in producing the TPM soil. Composting [93] and pyrolysis [94] of the raw manure as well as co-composting [95] of the raw manure with biochar are

Table 4
Selected manure properties.

Manure type	pH	Ca	K	Mg	P	C	N
		mg kg^{-1}				%	
Poultry manure	6.81	8.9	16.7	5.4	13.0	21.6	2.88
	7.05	41.3	12.9	6.2	37.5	20.5	5.46
Cattle manure	9.00	–	23.0	–	11.0	37.5	0.78
Goat manure	7.80	–	–	–	93.0	44.8	1.70
Sheep manure	7.90	–	7700	–	26,700	36.2	1.96
Fecal matter	6.74	3570	3840	1710	4290	37.2	3.10
Pig manure	6.68	–	–	–	18,888	37.9	3.01

Data sources: Agbede et al., [123]; Are et al., [139]; Harris [140]; Neina et al. [141]; Neina et al. [142]; Elouear et al. [143]; Rose et al. [99]; Singh et al. [144]; Bao et al. [145].

among many management options that can be used. These may decrease disease-causing organisms and odor, while potentially reducing litter volume and soil N losses as well as enhancing N retention [95] and recovery in crop-soil systems.

3.3.2.3. Faecal matter. Research shows that human excreta was a key source of N and P in the ADEs [24] because it was part of the materials that formed the ADEs [96]. Historically, human excreta have been a source of nutrients for crop production in backyard gardening. However, the health risks and cultural perceptions [97] may impede the utilization of human excreta. Fortunately, through ecological sanitation [98], human excreta have been utilized in some societies, although its sustainability and perpetuity seem to have been stalled in recent years. Among the human excreta, faecal matter contains the most pathogens, constituting about 25–54% microbial biomass [99]. In dealing with the pathogens, biochar could also be used to disinfect or co-compost the faecal matter [100] to play a similar role as wood ash [101]. It could also be used as a feedstock for biochar production [102]. Faecal matter is the partially digested organic material of excreta such as carbohydrate, fiber, protein, and fat depending on the diet [99]. Consequently, it contains less nutrients compared to urine and thus act as a soil conditioner [98] like biochar. Faecal matter is produced by all human beings on a daily basis amounting to about 25–50 kg dry matter per person per year [98,103,104]. The amount of nutrients that one person can produce per year is up to 0.55 kg N, 0.18 kg P and 0.37 kg P [98,104]. Based on the amount of nutrients extracted by one metric ton of yam tubers (Carsky and Tian, 1998) cited by Asiedu and Sartie [105], nutrients from faecal matter alone produced by about fifteen people per year could be used to produce one metric ton of yam and still leave nutrients in the soil to maintain the soil quality. The population of the top yam producers in West Africa stands at 309.1 million according to 2022 estimates [106]. With this huge population, ecological sanitation could be a strategy used to harness human excreta to supplement other organic wastes and biochar to produce TPM soil for yam production.

3.3.3. Other domestic wastes

3.3.3.1. Urine. Urine is a liquid excrement from the human body produced by the kidney and excreted through the urethra [99]. Urine contains significant amounts of major plant nutrients such as N, P and K [107]. Its composition depends on the individual, location, nutrient content of food consumed by the individual [108–110], health conditions [111], and the level of physical activity [112]. In a hot climate with high levels of perspiration, urine gets concentrated, whereas the consumption of large amounts of liquid dilutes urine [113]. High amounts of sweat may also result in N losses [114] in small amounts as urea [112]. According to Langergraber & Muellegger [103], a human being produces about 500 L of urine per year. Through urine-diverting toilets, urine can be collected and used in co-composting with fecal matter, other organic wastes and biochar for the TPM soil. Urine is composed of nitrogenous substances [107] (Table 5) aside Na^+, Cl^- and K^+ which are the most abundant ions (Table 5) in the body responsible for the maintenance of electrical charges [112]. Urine also contains heavy metals, but the content is generally lower than in faeces, inorganic fertilizers, kitchen wastes, and farm yard manure. Although urine has some health risks, the pathogenic risk can be eliminated through storage and co-composting. The urine can be used effectively via co-composting. De Gisi et al. [44] suggested that 40–65% of urine could be mix with 80% sawdust or wood chippings source, 10% ground charcoal power and 10% existing soil to serve as a source of moisture to enhance the biological transformation process.

3.3.3.2. Wood ash. Wood ash is a component of the ADEs which can also be incorporated in the TPM soil. It is a waste mostly found in West Africa kitchens and hearths. This does not in any way promote deforestation but to utilize waste generated on a daily basis. Wood

Table 5
Chemical characteristics of urine.

Property	Content (mg L^{-1})
Nitrogeneous compounds	
Urea (CON_2H_4)	9300–23, 300
Ammonia (NH_3)	200–730
Uric acid ($C_5H_4N_4O_3$)	40–670
Creatinine ($C_4H_7N_3O$)	670-2150
Creatine ($C_4H_9N_3O_2$)	0–530
Ions	
Sodium	1170–4390
Potassium	590-2610
Carbonates (CO_3^-)	100–150
Magnesium	20–205
Calcium	30–390
Bicarbonates (HCO_3^-)	20–560
Chloride (Cl^-)	1870-8400
Phosphorus	150-1070
pH	5–9.3*
Heavy metals	
Cu, Hg, Ni, Zn, Cr, Pb, and Cd	Very low

Data sources: Putman, [146]; Lentner et al., [147]; Creager [148]; Jönsson et al. [113]; Heinonen-Tanski et al. [149]. *This includes pH of stored urine.

ash is alkaline with a calcium carbonate equivalence ranging from 17 to 95% which makes it a liming material [115–117]. Generally, wood ash contains basic cations and P which gives it fertilizer qualities although it contains some trace elements [116,117]. Biochar and wood ash has similar characteristics except for the carbon content because of incomplete combustion gives biochar CEC and structural effects in soils.

4. How the terra preta model soil can be developed

4.1. Assumptions

To optimize the TPM conditions required for yam production, it is imperative to consider some basic issues or assumptions related to its formation. The following assumptions are considered:

a. The ADEs developed from virtually all types of soils which implies that TPM soils can be developed from all soil types. Incidentally, there are similarities in the soil types of tropical South and Central America and Central and humid West Africa [118]. The soils are generally of poor fertility. More so, biochar application produces the greatest crop yield response to biochar addition, particularly in soils of poor fertility or degraded soil conditions such as sandy texture, CEC (<10 cmol$_c$ kg^{-1}), SOC ≤ 20 g kg^{-1}, soil pH ≤ 6.5 [119].
b. The application of biochar produces integrated effects on the biological, chemical and physical properties of the soil similar to those of organic matter [2,19]. The ADEs do not contain only charcoal but charcoal intimately mixed with decomposable organic material. Therefore, it should be noted that sole biochar applications increases soil pH due to the high alkalinity compared to more stable pH from co-applications [120] depending on biochar feedstock and pyrolysis temperature. In previous studies, Steiner et al. [15] suggested that sole charcoal applications do not prove effective compared to the co-application of charcoal and organic amendments. This, they said might mimic the properties of ADE as nutrient losses in charcoal and organic treatments remained relatively stable. Earlier reviews suggest that the co-application of biochar with either organic or inorganic fertilizers enhance plant nutrient use efficiency leading to higher crop yields [15,121,122]. In a sandy Luvisol, Agbede et al. [123] obtained the best soil properties, growth, yields and nutrient quality of cocoyam from the combined application of 30 t ha^{-1} biochar (2 mm hardwood biochar produced using local charcoal kilns) and 7.5 t ha^{-1} poultry manure. They attributed these effects to the interactive enhancement of poultry manure by biochar, which improved the bulk density, porosity, moisture content, C, N, P and basic cation contents of the soil. In the same soil type, Agbede et al. [123] found the long-term (additive) effects of the same biochar type on maize yield. Generally, it has been observed that the magnitude of decrease in soil bulk density through the co-application of biochar and organic manures exceeds that of sole applications [123,124]. The reduction in bulk density has additive effects in subsequent years with values close to those of forest soils (i.e., 0.91–1.39 g cm^{-3}) and yam mound soils (i.e. 1.11–1.33 g cm^{-3}) [125]. For instance, biochar produced from an equal ratio of paper fiber sludge and grain husks produced at 550 °C and reapplied to a Haplic Luvisol at 20 t ha^{-1} without fertilizer reduced bulk density from 1.41 to 1.25 g cm^{-3} [126]. Similar to co-application, biochar co-composting produces synergy [15,127] by offsetting any negative effects of biochar and enhancing it efficiency [59,61]. Specifically, biochar co-composting tends to reduce pH [128] and N losses [100,127].
c. The capacity of biochar properties to modify soil properties depends on feedstock, pyrolysis temperature [67,68], specific native soil properties (e.g. pH, texture), biochar particle size and application rate [64,84]. The impacts tend to last for an additional year or produce additive effects in subsequent years [61,73,84,123,124]. The most important biochar properties (Table 2) relevant to creating the appropriate TPM soil properties for improvement in yam production include low bulk density, high CEC, high total alkalinity (enrichment of basic cations), and some significant amount of N (usually higher than in most tropical soils).
d. To obtain enough of the materials required for the TPM soil, immense efforts are needed. This implies in some instances, the materials may have to be transported over long distances which will involve extra costs.
e. The time required to form the TPM soil is likely to depend on climatic influences as stated in Fig. 1.

4.2. Development process

4.2.1. Fractions of materials

Apart from the black charcoal which was quantified in the ADEs, the fractions of the other components are unknown. Practically, different rates of biochar have been applied to soil and the basis for such rates is often unknown. Also, because black charcoal is the key to stabilizing SOM, it is important to start the TPM soil with it. Glaser et al. [47] found about 15–60 t ha^{-1} charcoal up to 30 cm depth in the ADEs but recommended about 1–3 t ha^{-1} for good yields. This seems reasonable. Considering the kind of deposition that took place in the ADEs, it is possible that the particle sizes of the black charcoal was not as small and uniform as those of the non-ADE chars. Hunt et al. [129] proposed a rate of between 5 and 20% v/v which is much higher than the previously proposed rate. Despite the recommended application rates, it is important to consider soil and biochar properties, the possible addition of wood ash, crop type and requirements as well as the prevailing climatic conditions. Sometimes, the biochar rate could also be dictated by the quantity of available decomposable materials aside from the aforementioned factors. The ratio of decomposable wastes biochar/charcoal to can be at least 2 to help counteract some adverse effects. If charcoal is included, then the amount of biochar should be reduced farther to avoid extreme pH change and associated shocks. Finally, urine could be used as a source of moisture to enhance decomposition either solely or diluted with water. This could be done repeatedly.

4.2.2. Formation

The nature of the ADEs suggests that the Amerindians invested a huge amount of materials of both domestic and occupational origin and time to produce them [30,31]. It appeared possible because of the agrarian lifestyle or huge dependence of the people on raw natural resources compared to the current dispensation where the larger population is shifting far from it. This presupposes that the formation of the TPM soil requires more intentionality, commitment, persistence and time. Therefore, the TPM soil can be form in the following ways:

i. Intermittent (mostly biennial) and long-term biochar-organic matter or manure co-applications;
ii. Intermittent (mostly biennial) and long-term applications of co-composted biochar; and
iii. Off-site TPM soil formation involving soil and the other materials. This option may be suitable for trench tillage options and sack farming.

4.3. Tillage options

Optimum yam yields cannot be obtained without proper tillage as yam tubers require low bulk density for expansion inside the soil. Therefore, tillage methods that could be used for the TPM soil include mounds, ridges, pits or trenches. Earlier research shows that mounds are not suitable for land space management as compared to ridges. Traditionally, yams can be planted in pits or trenches (30 cm × 30 cm × 30 cm) filled with good soil [130]. The TPM soil could be produced off-site, filled in the pits or trenches and intercropped with crops that can tolerate yam canopy [131]. In this case, shallow root crops that are not heavy feeders can be used. However, this requires further research to select the most appropriate crops. Another non-conventional way in which the TPM soil could be used is by sack farming [132,133] where the soil is produced off-site and filled in the sacks.

4.4. Proposed management

Although the TPM soil may have a long-term fertility [44], the heavy-feeding nature of yam may disrupt this longevity. Currently, there is little information on the degradation of ADEs except for a few based on farmers' experiences. For instance, Junqueira et al. [31] observed that over-intensification on ADEs involving nutrient-demanding crops could lead to the degradation. Coomes and Miltner [58] observed a decline in the fertility of old kiln site soils following on-site charcoal production, particularly regarding base saturation, available P, soil pH accompanied by elevated levels of Al and bulk density. This may be caused by the continuous cultivation of heavy-feeding root crops such as cassava [33]. Further, German [33] gave accounts of various reports regarding the sustainability of the ADEs and concluded that the ADEs are more sustainable because of (1) their longevity of quality, (2) resilience or self-regenerative capacity, and (3) Economic use of soil amendments.

To avoid degradation of the ADEs, some farmers recommended crop rotation as a good strategy to sustain them. The implementation of a crop rotation plan will require reliable data on specific crop requirements and nutrient uptake. The proposed tillage practices for yam production on the TPM soil offer opportunities to adopt rotation. Mounds and ridges are usually not reuse after yam harvest and be constructed to achieve suitable bulk densities for tube expansion. The inclusion of leguminous crops in the rotation plan will be an added advantage, since N-fixing bacteria in association with the leguminous plants will fix atmospheric nitrogen for plant use and soil fertility management.

5. Case studies of biochar in yam production and its significance for the model soil

Previous studies suggest that the effect of biochar application on yields lasts an additional year besides the year of application [84]. In a previous review [2], it was observed that yam yields depend heavily on the physical properties of the soil such as bulk density (Table 1) as well as the chemical and biological properties of soils. Such properties are also found in the ADEs (Table 1). Also, the ADEs were widely used for cassava [31,33], another "heavy feeding" [134] staple". Sadly, the use of biochar for yam production is limited. Therefore, we present the existing ones, and others on root crops. For instance, Akom et al. [135] applied wood shavings biochar at four application rates (i.e., 0, 5, 10 and 15 t ha^{-1}) and three fertilizer application rates (0, 30 and 60 NPK kg ha^{-1}) on *Dioscorea rotundata* (Poir) grown in a Ferric Acrisol in the Deciduous Forest agroecological zone. The results showed that biochar treatments generally produced the highest number of marketable yam tubers, particularly from the highest biochar application rate of 15 t ha^{-1}. However, this study did not include any organic matter as prescribed for the TPM soils.

Due to the limited data on biochar and yam yields, root crops with similar nutrient requirements as yam were also considered. For instance, Adekiya et al. [124] found the synergistic effect of the application of biochar and poultry manure on radish yield on a Luvisol grown in the Derived Savanna (Forest-Savanna transition) agroecological zone of Nigeria. The highest radish yield was obtained from the combined applications of 50 t ha^{-1} biochar and 5 t ha^{-1} poultry manure in two consecutive years. Still, on the same soil type and in the same agroecological zone, Agbede et al. [123] obtained the highest yields of cocoyam from the combined application of 30 t ha^{-1} biochar and 7.5 t ha^{-1} poultry manure with increasing returns in subsequent years. Similarly, Yuniwati and Karyanto [136] observed a significant 47% increase in the yield of cassava compared to the control from a combined application of 15 t ha^{-1} corn cob biochar and 180 kg of N (Urea), 36 kg of P (P_2O_5) and 50 kg ha^{-1} of (K_2O) in an Andisols in Indonesia. The biochar amendments also improved the quality of the soil by improving the physical and chemical properties of the soil. A real TPM case study involving soil, biochar, animal manure, waste charcoal, kitchen wastes, and wood ash is underway and will soon be published.

6. Conclusions and recommendations for future research

The TPM soil is not the business-*as*-usual of biochar use but an intentional integration of biochar use, ecological sanitation and "nutrient mining" in MSW management for sustainable sendentism. It is a promising model that may be useful not only for yam but for other crops as well. Integration makes a difference. A review of the available resources suggests that they can be harnessed for the purpose. However, harnessing all the different resources required to produce the TPM soil requires consciousness, zeal, commitment and corporation by all stakeholders to achieve this in the long term. The hurdles associated with the haulage of all the materials involved cannot be discounted given the existing poor transport infrastructure in West Africa. Even after jumping that hurdle, there is still the need to strategize the sustainable use of the TPM soils. The benefits of adopting the TPM theory include biodiversity conversation, enhance ecosystem services, improve urban waste management and sanitation, and improve the adoption of ecological sanitation.

The proposed is not in any way a silver bullet. It is likely to come with its own challenges depending on the location. This calls for further research interdisciplinary research to assess the cost-benefits of the TPM soil, socio-cultural dimensions, suitable ratios of biochar/charcoal and decomposable materials required for specific crop and soil types in different agroecological zones, adverse effects of ADEs and the TPM soil as well as their degradation. In addition to research, appropriate policies would have to be formulated to guide in the adoption of TPM soils as a support sustainable sedentary crop production.

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Data availability statement

No data was used for the research described in the article.

Additional information

No additional information is available for this paper.

Declaration of competing interest

The authors declare no conflict of interest.

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