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Interactive comment on "Origin, distribution, and characteristics of Archaeological Dark Earth soils – A review" *by* Michael O. Asare et al.

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The overall comments by the referee were very productive in upgrading our manuscript, which all have been addressed accordingly. Additional studies were also added to clarify the quantitative chemical properties of ABE compared to other reference values/Control

Abstract The abstract is introduced by directly relating Archaeological black earth to anthrosol according to FAO/WRB. "Archaeological black earth (ABE) can be classified as a layer of anthrosol (syn. anthroposol) visually characterized by black color mainly due to homogenous charcoal inclusion, and substantial enrichment by nutrients compared to surrounding soils". The main objective of the study has been added to the abstract of and all redundant parts have been omitted. "The study aimed to provide a detailed overview of the variability, distributions, and characteristics of ABEs relating to their classifications as well as the physicochemical properties".

Abbreviations Archaeological Black Earth in the text not starting a main sentence were rewritten as archaeological black earth and those starting as Archaeological black earth.

Introduction 44-46 Human influenced historical events, such as plants and animals' domestication and metallurgy, have been responsible for changes in natural landscapes (Peverill et al., 1999; Howard, 2017).

47-51 Many human activities are responsible for soil alteration; a blatant example is the creation of dark cultural horizons, mainly termed as archaeological black earth (ABE). They usually belong to anthropogenic soils, classified as Anthrosols (Howard, 2017; World Reference Base (WRB), 2015) or termed as HAHT (human-altered and human-transported) soils (Soil Survey Staff, 2015). ABE formation consisted of a deliberate and/or unintentional accumulation of layers because of settlement activities, wastes deposition, charred residues, bones, shells, and biomass ashes from prehistoric up to recent times. Such anthropogenic soils are usually characterized by higher concentrations in macro- (e.g., N, P, K, and Ca) and micronutrient (e.g., Mn, Cu, and Zn), that determines a difference in terms of main physical-chemical properties in comparison to neighboring (natural) soils" (Macphail et al., 2003; WinklerPrins, 2014; Nicosia et al., 2017).

Historical characterization of archaeological black earth

Terra preta 99-102 According to Lehmann et al. (2003b), Terra preta is found on a variety of soil reference groups such as Acrisols, Arenosols, Cambisols, Ferralsols, Latosols, Luvisols, Nitisols (WRB, 2015).

103-104

The areas where this soil occurs are well-drained, near running water, and located in some geographical regions (Sombroek, 1966), however, past human activities has significantly distinguished the elemental composition compared to neighboring soils.

African dark earth - Line 133 According to (Solomon et al., 2016) local inhabitants of areas with human-impacted dark earth in a study in Ghana and Liberia reported high crop yields compared to the surrounding soils.

3.1. Physicochemical properties of Amazonian Dark Earth line 178 Terra Preta is formed by a unique combination of intentional management of the soil for farming and unintentional outcome of human occupations and discard of wastes with various inputs of organic and inorganic materials (Glaser et al., 2001).

- lines 188-191 Several anthropogenic activities, e.g., the use of low heat, smoldering fires for food and pottery preparations, and spiritual reasons contribute to biochar accumulation or biochar amendments to home gardens, leading to the formation of Terra preta (Glaser et al., 2001). Thus, Terra preta formation is a combination of both unintentional soil modification as well as intentional amendments to improve small-scale home gardens. Therefore, this explains why the majority of Terra preta occupy a relatively smaller land size.

lines 195-202 According to Ricigliano, (2011) the profile of Terra preta can be physically divided into three; i) horizon A, representing a deep, dark, and nutrient-rich layer with an abundance of pottery fragments, lithics, and charcoal. ii) horizon B/B1, which is a transitional horizon with a large quantity of peds and root linings thickly coated in organic matter, and iii) the third horizon (B2) representing more thinly coated peds due to a lower percentage of organic matter with the soil lighter in color. However, in the field, Terra preta is identified by unusual features for Amazonian upland soils, such as topsoil with dark matrix colors (dark brown to black) at a variety of depth and presence of potsherds and lithic artifacts corroborated with the homogenous high amount of charcoal (Fig. 3a).

lines 203-207 Terra preta has been reported having 2 to 3 times increased content of Ca, K, Mg, Mn, Cu, and Zn in comparison to surrounding soils since their discovery in the 1860s and 70s (Smith, 1980; Glaser, 2007; WinklerPrins, 2014). Moreover, Kern et al. (1996) reported (in mg kg-1) 4900, 1810, 634, 393, and 208 total content of P, Ca, Mg, Mn, and Zn in Terra preta in an archeological site in Quatipuru, Pará, Brazil compared to P, 100; Ca, 500; Mg, 1000; Mn, 1000; Zn, 90; in control (Malavolta, 1976). On the same site, the fertility of the Terra preta was confirmed by 700 mg kg-1 extractable P (32% of total P) compared to < 5 mg kg-1 in control (Lehmann et al., 2003a).

Line-212 Terra preta has been reported to contain C content of up to 150 g kg-1, as opposed to 20 to 30 g kg-1in surrounding soils (Novotny et al., 2009). The C compounds in charcoal form loose chemical bonds with soluble plant nutrients so they are not as readily washed away by rain and irrigation. Even though charcoal addition to the soil has the potential to bind up N, it may not necessarily provide essential nutrients to the soil. It is, therefore, important to add a nutrient source, e.g., K and Mg along with charcoal amendments due to charcoal's high C: N ratio (Tenenbaum, 2009). Moreover, Lehmann et al. (2003a) studied Terra preta in Embrapa Amazônia Occidental, Brazil and reported significantly higher contents of C (84.7 g kg-1), P (318.4 mg kg-1), and Ca (32.8 mmolc kg−1) compared to 39.7, 8.1, and 14.7, respectively, of same elements in surrounding soil. The content of available P was 318.4 mg kg-1 compared to 8.1-24.1 mg kg-1 in control, even with the addition of mineral fertilizers, manure, and charcoal.

3.2. Physicochemical properties of African dark earth Studies carried out by Solomon et al. (2016) in Ghana and Liberia identified that AfDEs have a higher content of nutrients in comparison to surrounding soils. They determined from 400-450 Mg ha-1 organic matter stock in the AfDEs, representing enrichment approximately 200 – 300% compared to the surrounding soils (120-150 Mg ha-1). Plant-available N and P contents in the arable layer (0-.02 m) ranged from (in mg kg-1) 1-3 and 150-400, respectively, compared to about 0.5-1.9 and 5-60 in the surrounding soils. The contents of

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Ca K, and Mg were substantially higher in AfDE than in surrounding soils (Solomon et al., 2016). They recorded a pH range from 5.6 to 6.4 (moderately to slightly acidic) quite analogous to those noted in many studied Terra preta compared to 4.3-5.3 (very strongly to strongly acidic) in the control. There was significantly higher pyrogenic carbon (4.94-37.74%) and cation-exchange capacity (120-150 mmolc kg-1) in the AfDE sites, representing 2 – 26 and 1.4 – 3.6, respectively, enrichment compared to surrounding soils. And this contributed to the retention of the elements. Except for increased plant-available N which has been recorded in the study of AfDEs, the high pH, CEC, and increased content of C, P, Ca, Mg mimics that of Terra Preta and other types of ABEs. In a recent study of AfDE in Ghana, the content of total P , K, Ca, and Mn was (in %) 0.16- 0.65, 0.8- 1.44, 0.9-.02, 0.08- 0.27, respectively, higher than the control (Asare et al., 2020a). In addition to substantially higher plant-available P, K, Ca, S, Fe, Cu, and Zn in the AfDE compared to the control. The authors further recorded a significantly higher pH ranging from 6.1-6.9 in the AfDE compared to 4.4 in the control. Hence, the retention of the elements in the AfDE is related to reduced soil acidity.

3.3. Physicochemical properties of European dark earth Moreover, in comparing dark earth formed beneath the alluvial sediments, the dark earth soil horizons contained from 0.48 – 1.25% organic carbon when compared to the alluvial sediments of 0.43%. Further, N recorded in the dark earth horizons ranged from 0.07 – 0.112% but no content of N was recorded in the alluvial sediments. A pH value ranging from 6.6 to 8.2 has also been reported in EDE by Courty et al. (1989) and Nicosia et al. (2012). In the 10 - 11th century AD, Slavic settlement activities in the Wendland region, Northern Germany created dark patches of soil horizon in the settlement area. Multi-elemental analysis of this soil indicated significantly higher content of C, N, P, Ca, Mg, Na, Fe, Cu, Zn, Mn, Ba and, pH (H2O) ranging from 5.0 to 6.7 compared to neighboring soil (Wiedner et al., 2015). These soils related to the first millennium AD dark earth from settlement context (often urbanized), which is known from the site in post-Roman Britain (Macphail, 1983) and partly from the migration period and Viking age size in Scandinavia (Wiedner et al., 2015). EDE from an 8th-13th century AD hillfort settlement, Czech Republic was reported of 40, 350, 900, 100, 140, 100, 35, 40, 30 and 90% enrichment by total N (0.3%), P (0.34%), Ca (2.4%), Mn (0.065%), Fe (2.4%), Al (4.8%), Sr (0.012%), Rb (0.011%), Cu (40 mg kg-1), and Zn (110 mg kg-1), respectively, in comparison to the control (Asare et al., 2020b). The soil was 2.5, 2.4, 4.3, and 1.5 times enriched by plant-available (in mg kg-1) P (451), K (384), Ca (7494), and Mg (188), respectively, compared to the control. Although the reduced pH (6.5) contributed to the retention of the elements, physical parameters such as the relatively high fraction of silt and clay and homogenous distribution of charcoal were vital in providing high sorption for the elements.

3.4. Physicochemical properties of Kitchen middens

Migliavacca et al. (2013) confirmed that high total P content among soil samples ranged from 11409 – 30663 mg $kg-1$ and organic P content (up to 28423 mg $kg-1$) was due to the accumulation of organic matter in a garbage hole. The contrast between domestic activities and garbage accumulation is indicated by the highest values of the C: N ratio in the latter. Moreover, in a phosphate analysis in Piedras Negras, Guatemala, Parnell (2001), concluded that areas of highest phosphate content (> 100 mg $kg-1$) were areas with a high ceramic density as well as bone fragments, charcoal, shells, and artifacts indicative of a kitchen midden Pettry and Bense (1989) studied midden-mound soils in north-eastern Mississippi, USA. They confirmed that these soils were generally enriched in organic C (0.9-1.9%), exchangeable bases, and P (203 – 408 mg kg-1), Ca (11.3 – 15 cmol $kg-1$), and had wider C: N ratios (16.9 – 22.1) than the natural soil. They had abundant evidence of biological activities, pH ranged from 5.5 to 6.0 compared with pH (H2O) 5.2 or less in natural soils, and they contained 1 to 5% charcoal in volume. I

Discussion and wider perspectives have been combined

Conclusions and outlook The study revealed that the types of ABEs (Amazonian Terra preta, African Dark Earth, European Dark Earth, and kitchen middens) are distributed from tropics, moderate climatic zones up to the Arctic regions and relates with past human activities such as slash-and-char and disposition of excrements, shells, bones, and wood ashes. The principles leading to the physicochemical formation of ABEs are similar except for certain human activities peculiar to the cultural setting of the regions. The fertility of ABE is associated with stable organic matter stock, microbial abundance, as well as higher CEC, pH, and nutrient (C, N, P, Ca, Mn, Cu, Zn, Mn, Mg, Fe, Sr, Rb, and Ba) content. The retention of the nutrients relates to the fraction of the size of soil particles, suitable pH, and homogenous distribution charcoal, predominantly responsible for the black color.

Edited version of the manuscript is given below

Origin, distribution, and characteristics of Archaeological black earth soils- A review
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Abstract Archaeological black earth (ABE) can be classified as a layer of anthrosol (syn. anthroposol) visually characterized by black color mainly due to homogenous charcoal inclusion, and substantial enrichment by nutrients compared to surrounding soils. The study aimed to provide a detailed overview of the variability, distributions, and characteristics of ABEs relating to their classifications as well as the physicochemical properties. Archaeological black earth is distributed from the tropics (Amazonian Terra preta, African dark earth), moderate climatic zones (European dark earth) up to the Arctic (kitchen middens). All the types of ABE developed as a result of deliberate and/or unintentional deposition of domestic and occupational wastes, charred residues,

bones, shells, and biomass ashes from prehistoric up to recent times. ABEs exhibit optimum C: N ratio for effective mineralization, stable organic matter content, and higher CEC compared to surrounding soils. Archaeological Black Earths are characterized by slightly acidic to neutral soil reactions and a substantially enriched by C, N, P, Ca, Mn, Cu, Zn, Mn, Mg, Fe, Sr, Rb, and Ba in comparison to surrounding control. The unclear remains the level of ABEs enrichment by these elements as enrichment factors for different elements are based on different analytical approaches from plants-available up to total contents in the soil. Although generally highly productive, comparison of herbage production and crop yields between ABEs and natural soils are still rare. The distribution and persistence of anthropogenic activities leading to the formation of ABEs indicate that they are subject to continual formation.

Keywords Anthrosol; Biomass ashes; Charcoal; Physicochemical property; Terra Preta

1. Introduction Human influenced historical events, such as plants and animals' domestication and metallurgy, have been responsible for changes in natural landscapes (Peverill et al., 1999; Howard, 2017). Many human activities are responsible for soil alteration; a blatant example is the creation of dark cultural horizons, mainly termed as archaeological black earth (ABE). They usually belong to anthropogenic soils, classified as Anthrosols (Howard, 2017; World Reference Base (WRB), 2015) or termed as HAHT (human-altered and human-transported) soils (Soil Survey Staff, 2015). ABE formation consisted of a deliberate and/or unintentional accumulation of layers because of settlement activities, wastes deposition, charred residues, bones, shells, and biomass ashes from prehistoric up to recent times. Such anthropogenic soils are usually characterized by higher concentrations in macro- (e.g., N, P, K, and Ca) and micronutrient (e.g., Mn, Cu, and Zn), that determines a difference in terms of main physical-chemical properties in comparison to neighboring (natural) soils"; (Macphail et al., 2003; WinklerPrins, 2014; Nicosia et al., 2017). Archaeological Black Earths are physically characterized by black, dark brown, or dark grey color (Asare et al., 2020a, b). However, in some regions, soils from past human activities are light without any accumulation

of black soil organic matter. For example, although the large-scale accumulation of P, K, S, Zn, and Cu were in comparison to adjacent rangelands and arable fields, at Tel Burna in Israel, even more than 2000 years after its abandonment, the color of the soil was light gray (Šmejda et al., 2017). Thus, ABEs can hardly develop in semi-arid and arid regions because of the high decomposition rate of accumulated organic matter. The depth of the ABE horizon normally ranges from 0.4 to 0.8 m and can extend up to 1m or more (Courty et al., 1989; Macphail et al., 2003), with increasing depth indicating increasing longevity and intensity of settlement activities. Archaeological black earth soils have been studied by many authors (Runge, 1973; Mücher et al., 1990; van Smeerdijk et al., 1995) but were previously limited to visual descriptions of different organic and inorganic inclusions, archaeological features, artifacts, and post-depositional modifications. More recently, micromorphological analyses were used to determine the variability of ABEs concerning the position in local catena's, parent materials, and broader landscape locations (e.g., Glaser et al., 2003a, 2003bWoods et al., 2009). Other studies have emphasized the timescales involved in the creation of ABEs taking hundreds of years (Richter, 2007; Kawa and Oyuela-Caycedo, 2008). Today, multi-elemental techniques are used to quantify different elements in ABEs to trace specific ancient anthropogenic activities connected with the accumulation of these elements. For example, using different analytical tools such as X-Ray florescence (XRF) spectrometry for the determination of near-total contents of elements, inductively-couple plasma optical emission spectroscopy (ICP-OES) in connection with different extraction procedures for estimation of plant available up to total contents of elements (Nicosia et al., 2012). Although many papers studying ABEs are available from different regions, a review summarizing the distribution, evolution, and properties of different ABEs has never been published according to our knowledge. The aim of this review was, therefore, i) to provide an overview of different types of ABEs and their distributions, ii) to describe their physicochemical properties, and iii) to identify under-studied questions for the future development of new research activities.

2. Historical characterization of archaeological black earth

This part of the review discusses the widely studied ABEs from the tropics up to the arctic zones; Amazonian Dark Earth, African Dark Earth, European Dark Earth, and kitchen middens (middens). Except for middens, the other types have been designated by their regional names. The geographical distribution of ABEs motivated the compilation of different types from different parts of the world (Fig. 1). The black color of all the ABEs are anthropogenically influenced and does not contradict natural dark soils.

2.1. Amazonian Dark Earth Amazonian Dark Earth is attributed to the vanished complex civilization that once thrived during the Pre-Columbian settlements in the Amazon regions of South American. Recorded use of this soil date at least 5000 Cal Years BP, with the majority forming between 1000 – 2000 Cal Years BP (Whitehead et al., 2010). Statistical modeling indicates that more than 150 000 km2 representing 3.2% of the Amazon forest may harbor Dark Earth sites (McMichael et al., 2014). Amazonian Dark Earth soil is most widely studied in Brazil where they occupy relatively large areas with thick altered soil mantles and higher chemical fertility than the surrounding soils not affected by anthropogenic activities (Corrêa, 2007). These sites are known by designations such as black earth (Terra preta), Indian black earth (Terra preta de Indio), anthropogenic black earth (Terra preta antropogenica), and archaeological black earth (Terra preta arqueologica) collectively termed as Amazonian Dark Earths (Lehmann et al., 2003b). According to Lehmann et al. (2003b), Terra preta is found on a variety of soil reference groups such as Acrisols, Arenosols, Cambisols, Ferralsols, Latosols, Luvisols, Nitisols (WRB, 2015). Their extent is not large, most patches range in size from 2 to 350 ha with the majority being at the smaller end of that range. The areas where this soil occurs are well-drained, near running water, and located in some geographical regions (Sombroek, 1966), however, past human activities has significantly distinguished the elemental composition compared to neighboring soils. Terra preta rarely appears as individual classes of soil on soil maps of the region because of their generally small individual extent but are included in more spatially extensive soil classes.

2.2. African Dark Earth African Dark Earth (AfDE) are found around edges of nucleated villages and ancient towns in tropical regions of Africa (Solomon et al., 2016), typically in rain forest suggesting that verdant rainforest is long-abandoned farmlands and settlement sites enriched by the wastes created by ancient humans. In a first-time analysis of indigenous soil management system in West Africa, radiocarbon dating (14C) of black C (charcoal) found in most identified AfDEs indicated that these soils developed ca 115 to 692 cal Years BP (Solomon et al., 2016) the only dated AfDEs in Africa so far. The discovery of pottery fragments and charred remains of burnt wood from fires set by humans, along with organic macro-remains from crop residues, animal, and bones have been identified as components of AfDE (Asare et al., 2020a). However, Frausin et al. (2014), reported that only particular human activities are responsible for AfDE formation and are highly differentiated by gender. Women are directly engaged in the deposition of charred organic materials from oil palm processing and potash production which are the major contributing activities in the formation processes. AfDEs are spatial distributed across most tropical regions of the African landscape, especially rain forest zones of Ghana, Cameroon, Chad, Guinea, Congo, Malawi, Sierra Leone, Liberia, and rarely in Ethiopia (Fairhead and Leach, 2009) engineered mostly by shifting households and settlement practices. In a recent study by Asare et al. (2020a), the authors identified the influence of past settlement activities, including burning observed from ashy deposits and burnt palm kernel shells in the formation of AfDE in Ghana. Although several discoveries of charred materials and pottery fragments were identified in AfDEs by Frausin et al. (2014), their study was limited to the factors of formation processes and did not determine the age of these objects. However, oral histories and landscape mapping confirmed that these indigenous soil management practices created AfDE in ancient times and has continued up to the present day, probably older than had been known (Fraser et al., 2014; Solomon et al., 2016). Inhabitants of identified AfDE sites from ethnographic accounts lived several thousand years in nucleated villages with subsistence focused on farming, hunting, etc. Thus, most studied AfDEs have rural origins (Frausin et al., 2014) unlike European dark earth and Terra preta which traces its origin from ancient civilization (Nicosia et al., 2012; WinklerPrins, 2014). Until now, there are so studies reporting the prehistoric origin of AfDE. According to (Solomon et al., 2016) local inhabitants of areas with human-impacted dark earth in a study in Ghana and Liberia reported high crop yields compared to the surrounding soils.

2.3. European Dark Earth European dark Earth (EDE) is mostly found in the Roman or postâĂŘRoman urban contexts observed predominantly, if not exclusively, in Europe. In an archaeological context, EDE indicates urban dark-colored, poorly stratified units, often formed over several centuries, frequently rich in anthropogenic remains such as biomass ashes, bricks, bones, charcoal, mortar, tiles, and pottery (Figure 3c). Micromorphological analysis of EDEs has indicated that dumping of wastes (house sweeping, hearth functioning and maintenance, and more especially food preparation) is an activity commonly identified to contribute immensely to the formation of EDE (Nicosia et al., 2012). The latter has often developed from middening deposits, for example in open areas or within abandoned house shells. Several pedological studies on EDE has been conducted in most European countries in the 1980s and 90s. However, maiden studies appeared in early 1980 in Britain and later in Italy where the expression Terre Nere. In France, EDE studies on Terres Noires date back to the early 1990s (Gebhardt, 1997). The earliest studies on EDE in Belgium have been carried out since 1996 in the city of Ghent and later in Brussels (Stoops et al., 2001; Devos et al., 2016). Several articles based on comparisons between EDEs contexts in different European countries were published (Macphail, 2014; Nicosia and Devos, 2014; Asare et al., 2020b).

2.4. Kitchen Midden Kitchen middens are localized patches of dark-colored earth with artifact inclusion resulting from the deliberate deposition of food remain, domestic materials such as broken and exhausted tools as other human occupations (Hirst, 2017). Middens are named according to their major composition, e.g., bone midden. However, kitchen maiden may contain both a high proportion of bones and shells. Middens are found everywhere humans have lived and have been connected to the Mesolithic period, ca 12000 Cal Years BP (Hirst, 2017). The size of a kitchen midden is a function of population size and the length of time the site was active. Kitchen midden usually develops in non-urban areas, where people discard food and other domestic waste into the soil at the same place (Howard, 2017). Over many years or centuries of waste disposal, midden developed a thick black, organic-rich topsoil usually containing animal bones, mollusk shells, charcoal, ash, etc. and can be in the form of a mound, a pit, or a layer in stratigraphic of the soil. Midden may represent individual periods of settlement at a place. For instance, the different layers of kitchen midden found in Qajaa, Greenland represent three different periods of settlement (Hollesen et al., 2013). The first 120 cm thick layer from the bottom represents the Saqqaq people who lived at the site from around 2000 – 1000 BC, followed by 20 – 30 cm peat without evidence of human activity (1000 – 400 BC). This was overlaid by a 2 – 30 cm thick layer representing the hunters of the Dorset people living in the area from about 400 – 200 BC. The uppermost archaeological layer (in some places up to 1 m thick) has been dated to represent the last immigration of Eskimos to Greenland (The Thule people; 1200 –1750 AD).

3. Physicochemical characteristics of Archaeological black earth Generally, ABEs have been reported to exhibit unique physical and chemical characteristics in comparison to their neighboring soils. This section is an overview of the physicochemical attributes of the different types of ABEs discussed above.

3.1. Physicochemical properties of Amazonian dark earth Terra Preta is formed by a unique combination of intentional management of the soil for farming and unintentional outcome of human occupations and discard of wastes with various inputs of organic and inorganic materials (Glaser et al., 2001). There is a reported possibility that agricultural practices in home gardens contributed to the genesis of Terra preta (Hecht 2003; Schmidt and Heckenberger, 2009). In recent times, midden areas are used as home gardens or home gardens are used as trash areas by indigenous groups in the Amazon basin such as the Ameridians. Amendments of biochar to home gardens are responsible for the high amounts of black C. Therefore, Terra preta genesis can be explained by formation from midden areas and home garden agriculture as also practiced today (Fig. 2). Also, the repeated slash-and-burn of abandoned settlement sites could have produced Terra preta (Denevan, 1998). Several anthropogenic activities, e.g., the use of low heat, smoldering fires for food and pottery preparations, and spiritual reasons contribute to biochar accumulation or biochar amendments to home gardens, leading to the formation of Terra preta (Glaser et al., 2001). Thus, Terra preta formation is a combination of both unintentional soil modification as well as intentional amendments to improve small-scale home gardens. Therefore, this explains why the majority of Terra preta occupy a relatively smaller land size. According to Ricigliano, (2011) the profile of Terra preta can be physically divided into three; i) horizon A, representing a deep, dark, and nutrient-rich layer with an abundance of pottery fragments, lithics, and charcoal. ii) horizon B/B1, which is a transitional horizon with a large quantity of peds and root linings thickly coated in organic matter, and iii) the third horizon (B2) representing more thinly coated peds due to a lower percentage of organic matter with the soil lighter in color. However, in the field, Terra preta is identified by unusual features for Amazonian upland soils, such as topsoil with dark matrix colors (dark brown to black) at a variety of depth and presence of potsherds and lithic artifacts corroborated with the homogenous high amount of charcoal (Fig. 3a). The most extraordinary chemical characteristics of Terra preta is their high fertility because they have persisted in environments that generally have high rainfall and high humidity which facilitate soil organic matter mineralization and nutrient leaching. Terra preta has been reported having 2 to 3 times increased content of Ca, K, Mg, Mn, Cu, and Zn in comparison to surrounding soils since their discovery in the 1860s and 70s (Smith, 1980; Glaser, 2007; Winkler-Prins, 2014). Moreover, Kern et al. (1996) reported (in mg kg-1) 4900, 1810, 634, 393, and 208 total content of P, Ca, Mg, Mn, and Zn in Terra preta in an archeological site in Quatipuru, Pará, Brazil compared to P, 100; Ca, 500; Mg, 1000; Mn, 1000; Zn, 90; in control (Malavolta, 1976). On the same site, the fertility of the Terra preta was confirmed by 700 mg kg-1 extractable P (32% of total P) compared to < 5 mg kg-1 in control (Lehmann et al., 2003a). The unique nature of high C content in Terra preta is the key

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to the stability of the organic matter. The C found in Terra preta is aromatic (black or pyrogenic carbon) and other organic materials (biochar) that are likely a consequence of the incorporation of charcoal into the soil (Golchin et al., 1997). This initiates a set of biological and chemical processes that have confirmed increased soil organic matter, microbial biomass, and diversity, cation-exchange capacity (CEC), pH, and nutrient retention (Lehmann et al., 2003a, b; WinklerPrins, 2014). Terra preta has been reported to contain C content of up to 150 g kg-1, as opposed to 20 to 30 g kg-1in surrounding soils (Novotny et al., 2009). The C compounds in charcoal form loose chemical bonds with soluble plant nutrients so they are not as readily washed away by rain and irrigation. Even though charcoal addition to the soil has the potential to bind up N, it may not necessarily provide essential nutrients to the soil. It is, therefore, important to add a nutrient source, e.g., K and Mg along with charcoal amendments due to charcoal's high C: N ratio (Tenenbaum, 2009). Moreover, Lehmann et al. (2003a) studied Terra preta in Embrapa Amazônia Occidental, Brazil and reported significantly higher contents of C (84.7 g kg-1), P (318.4 mg kg-1), and Ca (32.8 mmolc kg-1) compared to 39.7, 8.1, and 14.7, respectively, of same elements in surrounding soil. The content of available P was 318.4 mg kg-1 compared to 8.1-24.1 mg kg-1 in control, even with the addition of mineral fertilizers, manure, and charcoal. Additionally, increased contents of total P and Ca have also been reported (Smith, 1980) as well as Zn and Mn (Arroyo-Kalin et al., 2009). In a similar study on the chemical signatures of Terra preta by Kern (1988), anomalous increase by total P, Ca, Zn, and Mn contents were recorded near the shores of the Trombetas-Nhamundá River. Kern (1988) correlated these data with the former human occupation of the area. Soil chemical analyses carried out in former areas used for dumping of household waste in three Terra preta sites in Cachoeira Porteira (Pará) recorded elevated levels of total, P, Ca, Mg, Zn, Mn, and organic C (Kämpf and Kern, 2005). Similar results were obtained for the Terra preta at Caxiuanã and in Pará, where the contents of total P, Ca, Zn, and Mn was significantly higher in comparison to surrounding soils (Kern, 1996). Some authors have worked on the chemical content of fragmented potteries found in the Terra preta in the Amazon Basin (Da Costa et al., 2011; Costa et al., 2013). Most of these studies revealed that areas with the highest density of pottery fragments coincide with the highest contents of elements such as Zn, Cu, Mn, Ba, and Sr. These elements are indicative of human occupation and thus related to domestic units such as cabins, food storage, food preparation, and food consumption areas. Thus, Terra preta relates to increased contents of organic C, P, Ca, Mg, Mn, and Zn regardless of soil type on which it was formed in contrast to the usually highly weathered and nutrient-poor surrounding soils. Terra Preta is characterized by reduced acidity with pH usually ranging from 5.2 to 6.4 (Falcão et al., 2009; WinklerPrins, 2014) in comparison with surrounding soils with pH ranging from 3.0 to 4.2 (Souza et al., 2016). Terra preta is characterized by higher moisture-holding capacity and CEC in comparison with surrounding soils (Sombroek, 1966; Smith, 1980). Souza et al. (2016) recorded higher CEC ranging from 33.4 to 41.9 cmol dm-3 in Terra preta in comparison to only 14.2 cmol dm-3 in the surrounding soil. The combination of land use and ecological factors that led to the formation of Terra preta is still not known with precision.

3.2. Physicochemical properties of African dark earth Processes that lead to the formation of AfDE are quite similar to those of Terra preta except for certain activities that are peculiar to African regions. Therefore, AfDE is human-made analogous to Amazonian Terra preta yet subject to the continual formation. Although the physical characteristics of AfDEs are analogous to those of Terra preta, representative profile in comparison to other surrounding profile indicates that AfDE is dark-colored with the accumulation of pyrogenic carbon (PyC) in these black piles of the earth extending to a depth of 1.80 m (Fig. 3b). Studies carried out by Solomon et al. (2016) in Ghana and Liberia identified that AfDEs have a higher content of nutrients in comparison to surrounding soils. They determined from 400-450 Mg ha-1 organic matter stock in the AfDEs, representing enrichment approximately 200 – 300% compared to the surrounding soils (120-150 Mg ha-1). Plant-available N and P contents in the arable layer (0-.02 m) ranged from (in mg kg-1) 1-3 and 150-400, respectively, compared to about 0.5-1.9 and 5-60 in the surrounding soils. The contents of Ca K, and Mg were substantially higher in AfDE than in surrounding soils (Solomon et al., 2016). They recorded a pH range from 5.6 to 6.4 (moderately to slightly acidic) quite analogous to those noted in many studied Terra preta compared to 4.3-5.3 (very strongly to strongly acidic) in the control. There was significantly higher pyrogenic carbon (4.94-37.74%) and cation-exchange capacity (120-150 mmolc kg-1) in the AfDE sites, representing 2 – 26 and 1.4 – 3.6, respectively, enrichment compared to surrounding soils. And this contributed to the retention of the elements. Except for increased plant-available N which has been recorded in the study of AfDEs, the high pH, CEC, and increased content of C, P, Ca, Mg mimics that of Terra Preta and other types of ABEs. In a recent study of AfDE in Ghana, the content of total P , K, Ca, and Mn was (in %) 0.16- 0.65, 0.8- 1.44, 0.9-.02, 0.08- 0.27, respectively, higher than the control (Asare et al., 2020a). In addition to substantially higher plant-available P, K, Ca, S, Fe, Cu, and Zn in the AfDE compared to the control. The authors further recorded a significantly higher pH ranging from 6.1-6.9 in the AfDE compared to 4.4 in the control. Hence, the retention of the elements in the AfDE is related to reduced soil acidity. Although AfDEs have been identified in small patches of landscapes in many African countries, their classification has generally been based only on physical description lacking proper dating and detailed chemical analysis.

3.3. Physicochemical properties of European dark earth Pedological studies of EDE have been based on the topsoil with very little knowledge on the subsoil. The physical description of EDE usually divides the depth of the soil into four distinct horizons with the upper horizon mostly made of midden materials in the form of charcoal, shell, bone, plaster, bricks, etc. (Table 1; Courty et al., 1989). Furthermore, Courty et al. (1989), categorized EDE from their studies in London into two stratigraphic units; the lower ‘pale Dark Earth’ unit and the upper ‘Dark Earth’ unit. The pale Dark Earth unit was found on the relict of Roman floor levels which contained Roman coins and burials and was crosscut by later Roman features including debris from burning, collapse, and decay of buildings. The upper layer was typically 20 to 90 cm thick but ranged up to 2 m in thickness and was characterized by blackish color (Fig. 3c). Notwithstanding, the stratigraphical classification (cultural layers) of EDE can be connected with different past settlements from different archeological timelines. Another important characteristic feature of EDE is the high degree of bioturbation observable in the thin section. On the other hand, part of the EDE results from soil formation on grassland, pasture, or abandoned areas in urban or protoâĂŘurban contexts. Typical features are enhanced organic matter, biogenic porosity, and earthworm granules. Human activities such as house sweeping, hearth functioning and maintenance, food preparation, construction, leatherworking, manuring, quarrying, metal production among others have contributed to the formation of EDE. Butchery and leatherâĂŘworking waste have been reported by Stoops et al. (2001) from the Dark Earth in the center of Ghent, Belgium, and is a typical component at the London Guildhall (Macphail et al., 2008). Nicosia et al. (2017) reported that pedo-features associated with Dark Earth are mostly the outcomes of the formation of carbonates, Fe/Mn (hydr) oxides, and/or phosphates. The most common carbonate pedo-features are typic calcite nodules and hypo-coatings, the calcite deriving from the natural parent material (e.g., calcareous alluvium), or the dissolution of ashes, plaster, or mortar. The presence of fecal material such as latrine wastes and coprolites, charcoal, pottery, and enhanced values of P, organic matter, and exchangeable basic cations in Brussels confirms the use of manure (Devos et al., 2009). Most EDEs have high biomass ashes and contain brick earth and mortar fragments. The availability of P and other elements are from the decomposition of plant materials, excrements, urine, ashes, bones or fish bones, and charcoal. Courty et al. (1989) reported an extremely high content of total P between 1.6 to 2.6% in London impacted by bone, feces, or plant decomposition. Nicosia et al. (2012) in using Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM/EDS) in Dark Earth in Florence, Italy revealed that the neoformations consisted predominantly of calcium-iron phosphates or calcium phosphates with associated iron oxides. They further discussed that there is a limited variability of most of the physicochemical characteristics such as organic C, N, CEC, base saturation, dithionite extractable Fe, and Mn with depth in Dark Earth. Moreover, in comparing dark earth formed beneath the alluvial sediments, the dark earth soil horizons contained from 0.48 – 1.25% organic carbon when compared to the alluvial sediments of 0.43%. Further, N recorded in the dark earth horizons ranged from 0.07 – 0.112% but no content of N was recorded in the alluvial sediments. A pH value ranging from 6.6 to 8.2 has also been reported in EDE by Courty et al. (1989) and Nicosia et al. (2012). In the 10 - 11th century AD, Slavic settlement activities in the Wendland region, Northern Germany created dark patches of soil horizon in the settlement area. Multi-elemental analysis of this soil indicated significantly higher content of C, N, P, Ca, Mg, Na, Fe, Cu, Zn, Mn, Ba and, pH (H2O) ranging from 5.0 to 6.7 compared to neighboring soil (Wiedner et al., 2015). These soils related to the first millennium AD dark earth from settlement context (often urbanized), which is known from the site in post-Roman Britain (Macphail, 1983) and partly from the migration period and Viking age size in Scandinavia (Wiedner et al., 2015). EDE from an 8th-13th century AD hillfort settlement, Czech Republic was reported of 40, 350, 900, 100, 140, 100, 35, 40, 30 and 90% enrichment by total N (0.3%), P (0.34%), Ca (2.4%), Mn (0.065%), Fe (2.4%), Al (4.8%), Sr (0.012%), Rb (0.011%), Cu (40 mg kg-1), and Zn (110 mg kg-1), respectively, in comparison to the control (Asare et al., 2020b). The soil was 2.5, 2.4, 4.3, and 1.5 times enriched by plant-available (in mg kg-1) P (451), K (384), Ca (7494), and Mg (188), respectively, compared to the control. Although the reduced pH (6.5) contributed to the retention of the elements, physical parameters such as the relatively high fraction of silt and clay and homogenous distribution of charcoal were vital in providing high sorption for the elements.

3.4. Physicochemical properties of Kitchen middens Middens are generally localized sites, ranging from < 0.5 to several hectares in size, and are unrestricted in their distributions. Kitchen middens usually form because of repeated dumping but may be created by a single ceremonial feast (Howard, 2017). The kitchen midden is analogous to Terra preta due to their accumulation of abundant archaeological debris and sometimes generically referred to as Dark Earth (Fig. 3d). The dark color of kitchen midden is due to prolonged anthropogenic influence mainly by the accumulation of half-burnt organic matter (Lima, 2001). In some cases, midden environments have excellent preservation of organic materials like wood, basketry, and plant food. Most

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studied kitchen middens have higher nutrients content in comparison to surrounding soils (Schaefer et al., 2004; Kämpf and Kern, 2005) which can be attributed to the presence of incompletely weathered nutrient sources and abundant pottery fragments. Eberl et al. (2012) observed that human activities including the preparation of pigments explained the obscure distribution of different elements. High P levels were useful to detect middens, but they provided incomplete data and required contextualization by comprehensive archaeological interpretations. Migliavacca et al. (2013) confirmed that high total P content among soil samples ranged from 11409 – 30663 mg kg−1 and organic P content (up to 28423 mg kg−1) was due to the accumulation of organic matter in a garbage hole. The contrast between domestic activities and garbage accumulation is indicated by the highest values of the C: N ratio in the latter. Moreover, in a phosphate analysis in Piedras Negras, Guatemala, Parnell (2001), concluded that areas of highest phosphate content (> 100 mg kg−1) were areas with a high ceramic density as well as bone fragments, charcoal, shells, and artifacts indicative of a kitchen midden Pettry and Bense (1989) studied midden-mound soils in north-eastern Mississippi, USA. They confirmed that these soils were generally enriched in organic C (0.9-1.9%), exchangeable bases, and P (203 – 408 mg kg-1), Ca (11.3 – 15 cmol kg−1), and had wider C: N ratios (16.9 – 22.1) than the natural soil. They had abundant evidence of biological activities, pH ranged from 5.5 to 6.0 compared with pH (H2O) 5.2 or less in natural soils, and they contained 1 to 5% charcoal in volume. In an analysis of the chemical signature of a late classic Maya residential complex, Guatemala increased content of P, Fe, Sr, Cu, Mn, and Zn coincided with specific pits identified as a midden area (Eberl et al., 2012). However, the content of metals such as Pb and Cd may reflect occupational wastes.

4. Discussion The review present for the first-time detailed characterization of different types of ABEs from different geographical locations (Table 2). There are diverse factors that contributed to their formation processes from different geographical locations, which are generally the same in all ABEs. ABEs have stable organic matter stock, optimum C: N ratio for mineralization and release of elements, higher pH, CEC, and

contents of C, N, P, Ca, Mg, Mn, Cu, Zn, Sr, and Ba mostly corroborated with a higher amount of charcoal compared to surrounding soils. The accumulation of the elements is predominantly due to the deposition of organic wastes and wood ashes. The depth of ABEs is influenced by the duration and intensity of ancient human activities. Studied ABEs across the world represent nutrient-rich landscapes resulting from ancient human activities. Different types of studied ABEs have the same principle of formation and similar chemical properties. However, many authors have used different methodologies to quantify the elemental composition of ABEs from Africa to arctic regions (Lehmann et al., 2003b; Nicosia et al., 2013; Solomon et al., 2016). These methodological approaches were focused on the quantitative analysis of plants-available nutrients using different extraction approaches or on the total content of elements in the soil using dry analytical methods of XRF. Although different methods were used, there was a clear pattern recorded by all approaches – an enrichment of ABEs by C, N, P, Ca, Mg, Mn, Cu, Zn, Sr, and Ba in comparison to surrounding soils. The question which is still unsolved is how large the enrichment for different elements is and ABEs as every researcher uses a different analytical approach which gives different enrichment factors. In this respect, the total content of elements gives clear enrichment factors as obtained values for different elements are less affected by soil properties and reactions. Plant available contents of elements are generally highly affected by pH; thus, extraction of the plant-available fraction can increase the unreliability of enrichment factors as most elements can relate to soil matrix and they may not be released by extractants. Measurement using XRF and ICP-OES for the total content of the element can be compared since they correlate strongly with high precisions (Šmejda et al., 2018). Different types of ABEs have a different date of origin and geographic location as well as other peculiar activities pertinent within the cultural setting of the site where they are formed (Nicosia et al., 2012; Frausin et al., 2014). However, the formation of Terra preta and AfDE are generally more analogous as they both represent human formed soil from the tropical regions especially the rainforest zone in contrast with poorly drained surrounding soils (Sombroek, 1966; Solomon et al., 2016). A scattered range of these soils exist but perhaps have a different designation as observed in some countries in Asia and the arctic regions or not studied at all, especially in some parts of Africa. The deposition of domestic wastes has been noted as a factor in the formation of ABEs. Meanwhile, this is a major factor contributing to the formation of kitchen middens thus, kitchen middens form part of all the types of ABEs. The increased pH and stability of high organic matter content of ABEs provide suitable conditions for the persistence of other elements, high CEC, favorable C: N ratio for effective mineralization to enable higher crop growth. Studies on ancient dark anthrosols using different dating approaches and elemental analysis have generally been conducted in different parts of the world. However, in many studies, the soil may either not be named as a type of ABE or lacked proper dating (Fenger-Nielsen et al., 2018). However, the physicochemical features of such soil are similar to most identified and studied ABEs. In a study by Fenger-Nielsen et al. (2018), in five artic archaeological sites in Greenland, extractable (in kg m-2) P (12.51-29.01), water-extractable nitrate (0.18-0.53), and ammonium (0.47-0.85) were 2 - 6 times higher in dark deposit compared to surrounding soils. The increased content of elements and the black color of soil resulted from past human activities. The cold, wet climate of the Arctic led to the extraordinary preservation of archaeological sites and materials that offer important contributions to the understanding of our common cultural and ecological history (Hollesen et al., 2018). They concluded that soil-vegetation interaction at archaeological sites is markedly different and less affected by the natural environment and regional climate variations. Although such a conclusion was made, crop and herbage production in ancient anthropogenically black soil in comparison to control are not well-known. The formation of ABEs on existing natural dark soils e.g., chernozems has also received a lot of attention recently. In Central Europe, there has been no consensus on the formation of Chernozems as they are not only formed under steppe conditions but may be formed under forest vegetation (Schmidt et al., 2002). Given the extent and agricultural importance of this soil type recent studies indicate that factors including vegetation burning for agricultural purposes and other anthropogenic activities could contribute to the formation of this soil. However, no absolute

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time and age of chernozems have been stated since radiocarbon dating from charred materials conducted only provided the mean ages of fire events and mean residence time of soil organic matter based on stratigraphic records which provided Holocene age spreading over 3700 years. However, in a study by Carsten and Thomas (2010) on anthropogenic pedogenesis of chernozems in Germany, they concluded that the black C was formed through natural or anthropogenic burning can only be speculated as to the widespread destruction of forests by extended human fire clearance during the Early Neolithic period is rather unlikely. Meanwhile, remarkable evidence exists that Neolithic settlements were mostly situated at the edges of black soil patches confirming the idea that black soils as relics of agriculture (Gehrt et al., 2002; Eckmeier et al., 2007). Therefore, chernozems have completely different formation histories with most of them still under discussion. These observations have raised opportunities for further investigation into their distribution, land-use history, and dating to obtain more conclusive findings. In tropical Asia, in the interior of Borneo, East Kalimantan, Indonesia, preliminary evidence exists that several sites exhibit similar characteristics of Terra preta; riverside location, dark color with few pieces of charcoal (10 cm radius), higher pH, C, P, and Ca, and improved soil fertility in comparison to neighboring soils (Sheil et al., 2012). However, the ages of these soils are yet unknown even though humans have been present in East Kalimantan for 10,000 years (Mcdonagh, 2003). Ethnographic accounts suggested that swidden farming, which primarily involves slash and burns, and rotational farming was practiced there. The existence of such proves indicate that several patches of ABEs have been left unstudied or unclassified in nucleated abandoned villages, reserve areas as much attention are mostly paid on urban dark soils.

5. Conclusions and outlook The study revealed that the types of ABEs (Amazonian Terra preta, African Dark Earth, European Dark Earth, and kitchen middens) are distributed from tropics, moderate climatic zones up to the Arctic regions and relates with past human activities such as slash-and-char and disposition of excrements, shells, bones, and wood ashes. The principles leading to the physicochemical formation of

ABEs are similar except for certain human activities peculiar to the cultural setting of the regions. The fertility of ABE is associated with stable organic matter stock, microbial abundance, as well as higher CEC, pH, and nutrient (C, N, P, Ca, Mn, Cu, Zn, Mn, Mg, Fe, Sr, Rb, and Ba) content. The retention of the nutrients relates to the fraction of the size of soil particles, suitable pH, and homogenous distribution charcoal, predominantly responsible for the black color. There is a strong call for research in the study of some aspect of ABEs. Even with distinguishable features of ABEs, compared to the surrounding soil, not much is known about ABE in some parts of the world, e.g., Asia and North America. The direct estimate of the positive effects of ABE on crop yield in comparison to surrounding soils has been done in few cases only on Terra preta, but not on other ABEs. Even though AfDEs are mostly used for crop production and are reportedly known for high yields, a practical comparison of yields with surrounding soils has not been performed. The opportunities for C sequestration and the reduction of Greenhouse gas emissions in ABEs are potentially important for detailed studies. Hence, systematic research into the origin, chemistry, crop nutrient uptake, production potential, and application of stable isotope analysis of ABEs is necessary to provide better insight and attention to this category of soil.

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