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Origin, distribution, and characteristics of Archaeological Dark Earth soils- A review

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Abstract

Archaeological Dark Earth (ADE) is a layer of anthrosol (syn. anthroposol) visually characterized by dark color mainly due to homogenous charcoal inclusion, and substantial enrichment by nutrients in comparison to surrounding soils. ADE is distributed from the tropics (Amazonian *Terra preta*, African ADE), moderate climatic zones (European ADE) up to the Arctic (kitchen middens). Although ADE soils have been studied also in other regions of the world, they have no special regional names. All types of ADE developed as a result of deliberate and/or unintentional deposition of domestic/occupational wastes, charred residues, bones, shells, and biomass ashes from prehistoric up to recent times. ADEs have optimum C: N ratio for effective mineralization, stable organic matter content, reduced acidity, higher CEC and C, N, P, Ca, Mn, Cu, Zn, Mn, Mg, Fe, Sr, and Ba content in comparison to surrounding soils. The unclear remains the level of ADEs 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 ADEs and natural soils are still rare. The distribution and persistence of anthropogenic activities leading to the formation of ADEs indicate that they are subject to the continual formation.

Keywords

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

1. Introduction

Different archaeological timeline events by humans such as the domestication of plants and animals and metallurgy have been implicitly connected with deliberate and inadvertent changes to natural landscapes (Peverill et al., 1999; Howard, 2017).

These and other ancient human activities altered the soils by often creating dark cultural horizons termed in archaeological context as Archaeological Dark Earths (ADEs). Archaeological Dark Earth is an

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anthropogenic soil which reportedly exhibits higher contents of elements accumulation due to settlement activities (termed as anthropogenic elements) and by alteration of many chemical properties in comparison to neighboring soils (Macphail et al., 2003; Nicosia et al., 2012; WinklerPrins, 2014; Nicosia et al., 2017). ADEs are physically characterized by black, dark brown, or dark grey color. 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 recorded, 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, ADEs can hardly develop in semi-arid and arid regions probably because of the high decomposition rate of accumulated organic matter.

The depth of the ADE 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 Dark Earths 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 ADEs concerning the position in local catena's, parent materials, and broader landscape locations (e.g., Glaser et al., 2001, 2003a, 2003b; Lehmann et al., 2003b; Woods et al., 2009). Other studies have emphasized the timescales involved in the creation of ADEs taking hundreds of years (Richter, 2007; Kawa and Oyuela-Caycedo, 2008). Today, multi-elemental techniques are used to quantify different elements in ADEs 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

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plant available up to total contents of elements (Nicosia et al., 2012).

Although many papers studying ADEs are available from different regions, review summarizing the distribution, evolution, and properties of ADEs has never been published according to our knowledge. The aim of this review was, therefore, i) to provide an overview of different types of ADEs 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. Origin and distribution of the types of Archaeological Dark Earth

This part of the review discusses the most studied ADEs 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 dispersed geographical distribution of ADEs motivated the compilation of different types from different parts of the world (Fig. 1). The black color of all ADEs are anthropogenically influenced and do not contradict with 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 km^2 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

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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). *Terra preta* is found on a variety of soil types such as Acrisols, Arenosols, Cambisols, Ferralsols, Latosols, Luvisols, Nitisols, and Podzols classified according to World Reference Base (WRB) for Soil Resources (Lehmann et al., 2003b). 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 from which surrounding areas can be observed (Sombroek, 1966). *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 (^{14}C) 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) probably the only dated AfDEs in Africa.

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. 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. This is evident in the spatial distribution of AfDE

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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) mostly engineered by shifting households and settlement practices. 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 of AfDE 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). However, local inhabitants of areas with patches of human-impacted dark earth report of concomitantly high crop yields when compared to their surrounding soils (Solomon et al., 2016)

2.3. European Dark Earth

European dark Earth (EDE) is mostly found in the Roman or post-Roman 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

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90s. However, maiden studies appeared in the 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., 2009, 2016). Several articles based on comparisons between EDEs contexts in different European countries were published (Nicosia et al., 2013; Macphail, 2014; Nicosia and Devos, 2014).

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

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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 Dark Earths

Generally, ADEs 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 ADEs discussed above.

3.1. Physicochemical properties of Amazonian Dark Earth

There are two general hypotheses for *Terra preta* formation which are complementary: (i) *Terra Preta* was formed from an unintentional outcome of human occupations and discard of wastes with various inputs of organics (including mammal and fish bones, excrements, and biochar) and inorganic materials (such as ashes), and further debris. (ii) The outcome of the intentional management of the soil for farming. 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 probably 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 other anthropogenic activities such as the use of low heat, smoldering fires for food and pottery preparation, spiritual reasons, or biochar amendments to home gardens could also be responsible for biochar accumulation and subsequent formation of this soil type (Glaser et al., 2001). Thus, *Terra preta* formation is likely a combination of both unintentional soil modification as well as intentional amendments to improve small-scale home

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gardens. This probably explains why the majority of *Terra preta* belong to the smaller range in terms of the land sizes they occupy.

General physical description of *Terra preta* divides the profile into three distinct horizons (Ricigliano, 2011); i) A deep, dark, and nutrient-rich layer with a sandy texture and abundance of pottery fragments, lithics, and charcoal. ii) A transitional horizon with a large quantity of peds and root linings thickly coated in organic matter, and iii) the third horizon representing more thinly coated peds due to a lower percentage of organic matter with the soil lighter in color. In the field, they are 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 the 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 elements in comparison to surrounding soils since their discovery in the 1860s and 70s (Smith, 1980; Lehmann et al., 2003a, b; Glaser, 2007; WinklerPrins, 2014).

The unique nature of high C content in *Terra preta* is the key 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 (Glaser et al., 2003a; 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^{-1} in 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

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may not necessarily provide essential nutrients to the soil. It is, therefore, important to add a nutrient source along with charcoal amendments due to charcoal's high C: N ratio (Tenenbaum, 2009).

Moreover, Lehmann et al. (2003a), studied on *Terra preta* in Greenhouse Facilities of Embrapa Amazônia Occidental, Brazil and reported high contents of C, P, Ca, Zn, Cu, and Mn in comparison with surrounding soils. 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 relatively 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 were much 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 concluded that AfDE store 200 – 300% more organic carbon than their surrounding soils. Moreover, 2 – 26 times greater pyrogenic carbon (PyC), 1.4 – 3.6 times greater cation exchange capacity, 1.3 – 2.2, and 5 – 270 times more plant-available N and P respectively were also recorded in the AfDE site in comparison to surrounding soils. The contents of Ca, Mg, and K were 2 – 37, 1 – 20, and 1 – 4 times greater in AfDE than in surrounding soils respectively (Solomon et al., 2016). They recorded a pH range from 5.6 to 6.4 quite analogous to those noted in many studied *Terra preta.* Except for increased plant-available N which has been recorded in the study of AfDEs, the high pH and CEC increased content of soil C, P, Ca, Mg mimics that of *Terra Preta* and other types of ADEs. Although, AfDEs have been identified in many African countries and as small patches of landscapes within some of these countries, their classification has generally been based only on physical description lacking proper dating and chemical analysis.

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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).

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 proto-urban 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 leather-working 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 of exchangeable basic cations in Brussels confirms the use of manure (Devos et al., 2009). Most EDEs have

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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 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. A pH value ranging from 6.6 to 8.2 has 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 increased content of C, N, P, Ca, Mg, Na, Fe, Cu, Zn, Mn, and Ba with pH (H_2O) ranging from 5.0 to 6.7 (Wiedner et al., 2015). These soils related to the first millennium AD dark earth from (often urbanized) settlement context 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)

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 as a result 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

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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 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 probably abundant pottery debris. 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 higher total P and organic P distributions were due to the accumulation of organic matter in a garbage hole. The contrast between domestic activities and garbage accumulation as 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 concentration 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 matter, exchangeable bases, and P, and had wider C: N ratios and a higher CEC, than the natural soil. They had abundant evidence of biological activities, pH ranged from 5.5 to 6.0, compared with pH (H_2O) 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 waste.

4. Wider perspectives

Studies on ancient dark anthrosols using different dating approaches and elemental analysis have

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generally been conducted in different parts of the world. Other than the above- mentioned and discussed ADEs, the scope of many of such studies may either not named the soils as ADEs or lacked proper dating of such ancient sites (Fenger-Nielsen et al., 2018). However, the physicochemical features of these sites are sometimes the direct replicas of most recognized and studied ADEs.

In a study by Fenger-Nielsen et al. (2018), in five artic archaeological sites in Greenland, 2 - 6 times plant-available P, water-extractable nitrate and ammonium and plant available form of other elements were recorded in dark archaeological deposit in comparison to surrounding soils. The increased content of elements and the black color of soil resulted from past human activities. However, their study was focused on the spectral properties of vegetation in archaeological sites, concluding that soil-vegetation interaction at archaeological sites is markedly different and less affected the natural environment and regional climate variations. The cold, wet climate of the Arctic probably has 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).

The formation of ADEs 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 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

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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 about 10 cm radius, higher pH, C, P, and Ca, and improved soil fertility in comparison to neighboring soils (Sheil et al., 2012). However, the age of these soils has not been determined 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 can indicate that several patches of ADEs have been left unstudied or unclassified in nucleated abandoned villages, reserve areas as much attention are mostly paid on urban dark soils.

4. Discussion

In this review, we presented for the first-time detailed characterization of different types of ADEs from different geographical parts of the world (Table 2) as published reviews have not yet been done. There are diverse factors that contributed to their formation processes from different geographical locations which are generally the same in all ADEs. ADEs have stable organic matter stock, optimum C: N ratio for effective mineralization and release of the element, higher pH, CEC, and higher contents of C, N, P, Ca, Mg, Mn, Cu, Zn, Sr, and Ba mostly corroborated with a high amount of charcoal in comparison to

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surrounding soils. The accumulation of these elements is predominantly due to the deposition of organic wastes and wood ashes. The depth of ADEs is influenced by the duration and intensity of ancient human activities. Studied ADEs across the world are a representation of nutrient-rich landscape resulting from ancient human activities.

Different types of studied ADEs have the same principle of formation and the same or similar chemical properties. However, many authors have used different methodologies to quantify the elemental composition of ADEs 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 ADEs 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 ADEs 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 ADEs 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).

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The deposition of domestic wastes has been noted as a factor in the formation of ADEs. Meanwhile, this is a major factor contributing to the formation of kitchen middens thus, kitchen middens are probably part of all the types of ADEs. The increased pH and stability of high organic matter content of ADEs provide suitable conditions for the persistence of other elements, high CEC, favorable C: N ratio for effective mineralization to enable higher crop growth.

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.

5. Conclusions and outlook

We found that:

i) The types of ADEs (Amazonian *Terra preta*, African Dark Earth, European Dark Earth, and kitchen middens) are distributed from tropics, moderate climatic zones up to the Arctic regions of the world and relates with past human activities such as slash-and-char, organic waste disposal including excrements, shells, bones, and wood ashes. The principles leading to the physicochemical formation of ADEs are similar except for certain human activities peculiar to the cultural setting of the regions where ADEs are formed.

ii) Archaeological Dark Earths have sustained fertility associated with stable organic matter stock, microbial abundance, as well as higher CEC, pH, and nutrient content with homogenous dark color predominantly due to charcoal inclusion than their surrounding soils. Other studies have indicated the distribution of ADEs in different locations but lack regional names.

iii) ADEs have higher C, N, P, Ca, Mn, Cu, Zn, Mn, Mg, Fe, Sr, and Ba content than surrounding soils. ADEs have pH ranging from moderately to slightly acidic due to the liming effect of high Ca and adequate C: N ratio for effective mineralization. The depth, stratigraphy, and material composition of a specific form of ADE relates to the duration, intensity, and type of

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ancient human activities. The black color of *Terra preta*, AfDE, EDE, and kitchen middens are due to the addition of charcoal.

iv) There is a strong call for research in the study of some aspect of ADEs. Even with distinguishable features of ADEs, in comparison to the surrounding soil, not much is known about ADE in some parts of the world, e.g., Asia and North America. The direct estimate of the positive effects of ADE on crop yield in comparison to surrounding soils has been done in few cases only on *Terra preta*, but not on other ADEs. 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 ADEs are potentially important for detailed studies. Hence, the systematic research into the origin, chemistry, crop nutrient uptake, production potential, and application of stable isotope analysis of ADEs is necessary to provide better insight and attention to this category of soil.

Author contributions.

MOA conceived and executed the research and wrote the paper. JOA gave suggestions about the approach and wrote the paper. MH gave suggestions about the approach. All authors reviewed the paper.

Competing interests.

The authors declare that they have no conflict of interest.

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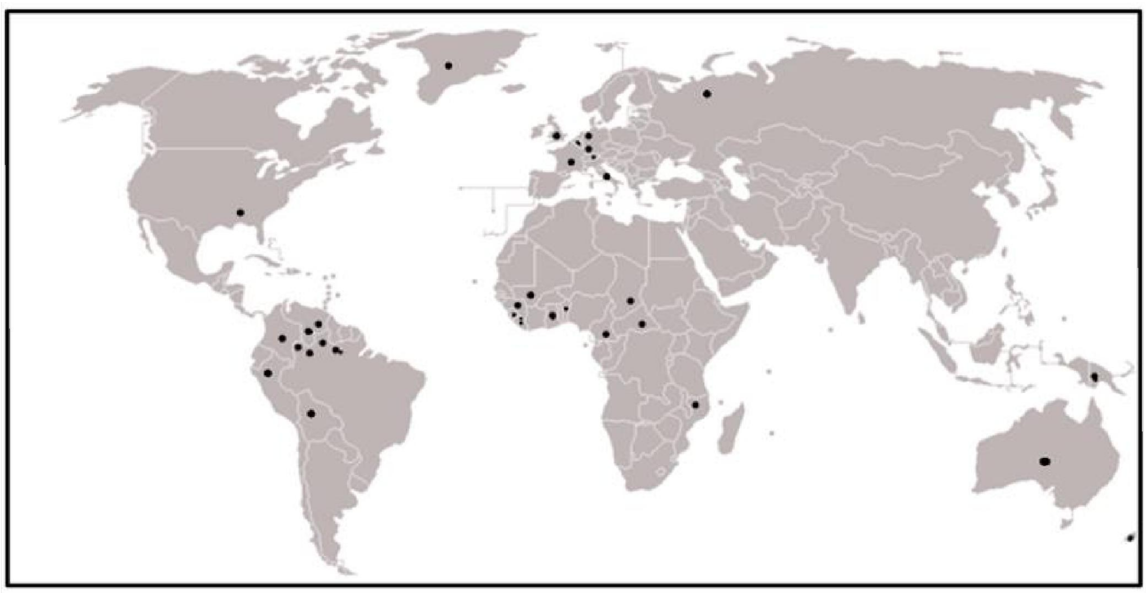

Fig. 1 Geographical distribution of Archaeological Dark Earths across the world. Dark spots within the map indicate countries where Archaeological Dark Earths have been identified and/or studied.

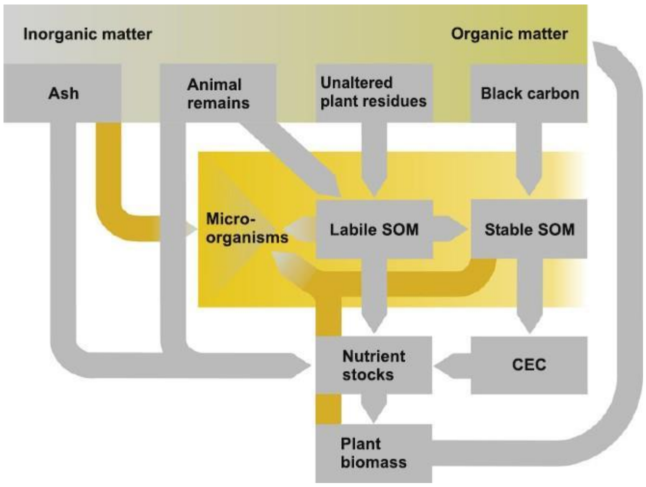

Fig. 2 Model of *Terra preta* genesis showing the elements of formation (ash, animal remains, unaltered plant residues, and black carbon) with their respective inputs to the soil below them (source: Glaser and Birk, 2011).

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Fig. 3 Typical examples of the different types of Archaeological Dark Earth. (a) Amazonian Dark Earth (*Terra preta*) from Hatahara (Central Amazon), a large pre-Columbian settlement situated at the confluence of the Amazon and Negro rivers (Source: Manuel Arroyo-Kalin). (b) Profile pit of African Dark Earth (right), reaching a depth of 1.80 cm and Oxisol (left - infertile background soil) from Liberia. The two pits are 20 m apart (source: Frausin et al., 2014). (c) Profile of European Dark Earth, in the Nordic regions of Germany (source: Wiedner et al., 2015), and (d) Kitchen midden (in Blacksod Habour on the mullet of Peninsula) - surface used for disposal of kitchen wastes and Shells, often characterized by dark stain or accumulation of debris (photo by Peter Foss)

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Table 1 Typical profile description of European Dark Earth from London, England with the *A horizon showing material inclusion during formation and different horizons showing their respective characteristics. A similar profile description is found in other parts of Europe but on different soil types

Horizon	Depth (cm)	Description	
*A	0-70	Exceedingly uniform and very dark grey sandy clay loam; weak coarse subangular blocky structure; coarse fragments and artifacts e.g., charcoal, oyster shell, bone, pottery, brick earth, mortar fragments; common root channels and earthworm burrows; clear smooth boundary.	Upper Dark Earth unit (Proper Dark Earth)
*B	70-85	Very dark greyish-brown, sandy loam; massive structure; firm; abundant brick earth and mortar fragments; few roots channels and earthworm burrows; clear smooth boundary	Upper Dark Earth unit (Proper Dark Earth)
*B	85-95	Strong brown slit (brick earth); massive structure, abrupt smooth to the wavy boundary. Represents Roman earthworks, i.e. floor, wall, or mortar foundation of building.	Pale Dark Earth unit
*C	95-135+	Light brown gravelly sand with common Fe concentrations as nodules, few artifacts (charcoal), common root channel	Pale Dark Earth unit

*Horizon designations (Adopted and modified from Courty et al. 1989).

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Table 2 Studies on a detailed description of different types of Archaeological Dark Earth.

Types of ADE	Origin/period	Ancient human activities	Avg. pH, Other chemical properties	References
Amazonian Dark Earth	South America (5000 cal Years BP)	Human occupation, heating, slash-and-burn agricultural practices, smoldering fires for food, and pottery preparation.	pH (5.2 - 6.4), High CEC, C, N, P, Ca, Zn, Cu, Mn, Ba, Sr	Kern et al. (1999); Glaser, (1999); Lehmann (2003a and b); Hecht (2003); Schmidt and Heckenberger (2009); Costa et al. (2013); WinklerPrins (2014)
African Dark Earth	Mostly tropical African Regions (115–692 cal Years BP)	Char materials, animal-based organic inputs e.g., bones from food preparation; harvest residues from plant-biomass, deposition of domestic refuse such as palm thatch, palm-fruit heads, rice straw, oil palm processing, and potash production.	pH (5.6 - 6.4), High CEC, C, N, P, K, Ca, Mn	Frausin et al. (2014); Fraser et al. (2014); Solomon et al., (2016)
European Dark Earth	Europe (Roman to post Roman period)	Debris from burning, collapse and decayed buildings, house sweeping, hearth functioning and maintenance, food preparation, leatherworking, manuring, quarrying, metal production, and butchery.	pH (5 – 8.2), High CEC, C, N, P, Ca, Mn, Fe	Courty et al. (1989); Nicosia et al. (2012); Wiedner et al. 2015
Kitchen Midden	Localized; part of the Arctic zone (ca 12000 cal Years BP)	Deposition of domestic wastes associated with food preparation; human occupation such stone, bones, and shells artifacts; human burials, hearth, and housing structures.	pH (5.5 - 6), High CEC, P, Ca, Mn, Mg, Cu, Zn	Kämpf and Kern (2005); Eberl et al. (2012); Hirst (2017)