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Mapping of Selected Ivorian Clays and Their Valorization Potential: A Comprehensive Review

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Abstract

This review brings together what is currently known about the distribution, mineralogy, physicochemical properties and valorization of clay resources in Côte d'Ivoire (Ivory Coast). The country has sizeable clay deposits spread over very different geological settings: coastal sedimentary basins, humid forest plateaus and the lateritic zones of the savannah belt. Kaolinite, illite and smectites (mostly montmorillonite) are the main clay minerals, usually accompanied by quartz and iron oxides (goethite, hematite). Grain-size distribution, plasticity, cation exchange capacity (CEC) and specific surface area largely control how these materials perform in practice. Kaolinite stands out for its thermal stability, which suits it to ceramics and eco-construction. Smectites adsorb strongly and are therefore good candidates for water treatment and catalysis, while illite sits in between, with moderate mechanical and adsorptive behavior. We reviewed the following valorization routes: compressed earth bricks, partial replacement of clinker by pozzolanic calcined clays, adsorption of organic and inorganic pollutants, traditional and modern pharmaceutical uses, advanced oxidation processes (AOPs), and bioplastics reinforced with metakaolin. Industrial exploitation nonetheless remains limited. Deposits vary widely from one site to another, no harmonized national inventory exists, published data are scattered, and logistical and regulatory obstacles add to the difficulty. We therefore recommend a national strategy built on systematic re-

source mapping, standardized analytical procedures, a database of reference samples and pilot-scale valorization projects. Ivorian clays can support industrial diversification and sustainable development, but only if their exploitation rests on a coherent scientific, technical and institutional framework.

Keywords

Clay Minerals, Côte d'Ivoire, Geological Mapping, Kaolinite, Smectite, Valorization, Ceramics, Water Remediation, Bioplastics, Eco-Construction

1. Introduction

Clays are a resource of real economic and scientific weight. They serve as raw materials for ceramics, construction, chemical engineering, pharmacy and environmental remediation. Strictly speaking, clays are natural materials made mostly of hydrated aluminium phyllosilicates with a layered crystal structure; kaolinite, montmorillonite, illite and related minerals belong to this family [1]-[3]. In the natural state, they can be loose or, once wet, plastic, and depending on their mineralogy they may dry, adsorb, bind or resist heat.

The range of uses of clays is well documented. In building, compressed earth bricks and ceramic blocks offer a cheap and thermally efficient alternative to conventional materials [4] [5]. For water treatment, the porous structure and reactive surface of smectitic clays allow them to remove heavy metals, synthetic dyes and organic micropollutants [6] [7]. Clay-based materials modified with metal cations or nanoparticles have also shown promising activity in advanced oxidation processes (AOPs) aimed at recalcitrant pollutants [8]. Some Ivorian clays are traditionally eaten for their protective effect on the gut and their antibacterial action [9] [10]. More recently, cassava starch bioplastics reinforced with metakaolin have opened a route towards sustainable packaging [11] [12].

Côte d'Ivoire has a rich but largely unexploited stock of clay, found in all of its physiographic regions. The Société pour le Développement Minier (SODEMI) located many clay occurrences across the country during its exploration campaigns. Later studies showed that kaolinite and illite dominate these deposits, with smectites in some localities and variable amounts of iron oxides such as goethite and hematite [13]-[15]. Several regional studies have looked at the geometry, chemistry and mineralogy of kaolinitic and smectitic deposits. A national synthesis, however, is still missing.

For a long time, Ivorian clays were used mainly for pottery, cosmetics and geophagy. Today they attract serious scientific and industrial attention. This review has four aims: (i) to map how clay resources are distributed over the national territory; (ii) to describe their main mineralogical and physicochemical properties; (iii) to present, and critically assess, a selection of valorization routes reported in the literature; and (iv) to identify what currently holds back exploitation and to suggest strategic recommendations for sustainable use.

2. Methodology

We followed a systematic approach to the literature search, using Scopus, Web of Science, Google Scholar and the institutional repositories of Ivorian universities. Queries combined the terms "clay", "argile", "Côte d'Ivoire", "Ivory Coast", "kaolinite", "montmorillonite", "illite", "smectite", "valorization", "mineralogy", "mapping", "characterization", "construction", "adsorption" and "bioplastics". No language restriction was applied. The search covered documents published between 2000 and 2024, the period in which most of the retrieved literature was concentrated. The initial search returned [12] records. After duplicates were removed and titles and abstracts screened, [2] records were excluded because they did not deal with clay deposits from Côte d'Ivoire or had no original mineralogical, physicochemical or applied-valorization data, which left 23 records for full-text review and inclusion. A study was kept if it reported original geological, mineralogical, physicochemical or applied-valorization data on clays explicitly sourced from Côte d'Ivoire. We excluded studies on clays from other countries, purely theoretical mineralogical texts without Ivorian data, and non-peer-reviewed sources whose data could not be independently checked. Data from the retained documents were extracted, critically assessed and synthesized by theme.

For the geographic synthesis in Section 3.3, locality name, main clay type and coordinates were taken directly from each cited primary source. When a source gave a locality but no coordinates, we entered "N/A" in the coordinate field instead of estimating or interpolating a position, so that no positional uncertainty would be introduced that the original authors never had. The distribution of clay application fields is shown schematically in **Figure 1**, and the geographic distribution of the deposits in Côte d'Ivoire, compiled from these sources, is shown in **Figure 2** and **Figure 3**.

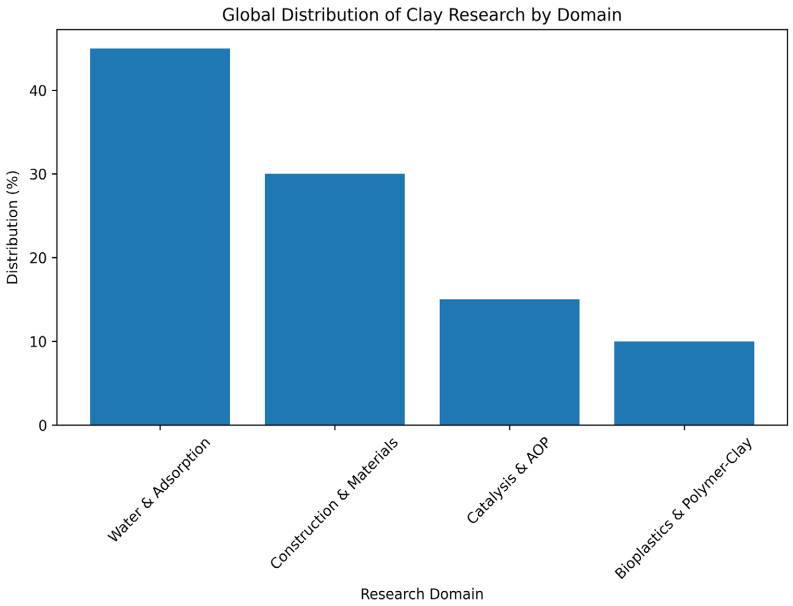

Figure 1. Global distribution of the application fields of clays in Côte d'Ivoire.

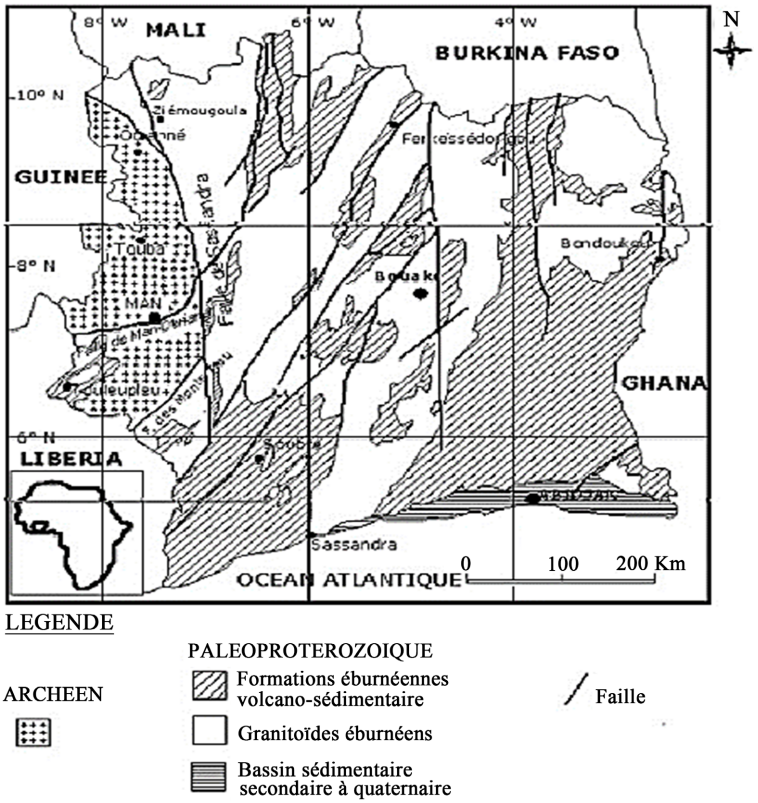

Figure 2. Geological map of Ivory Coast.

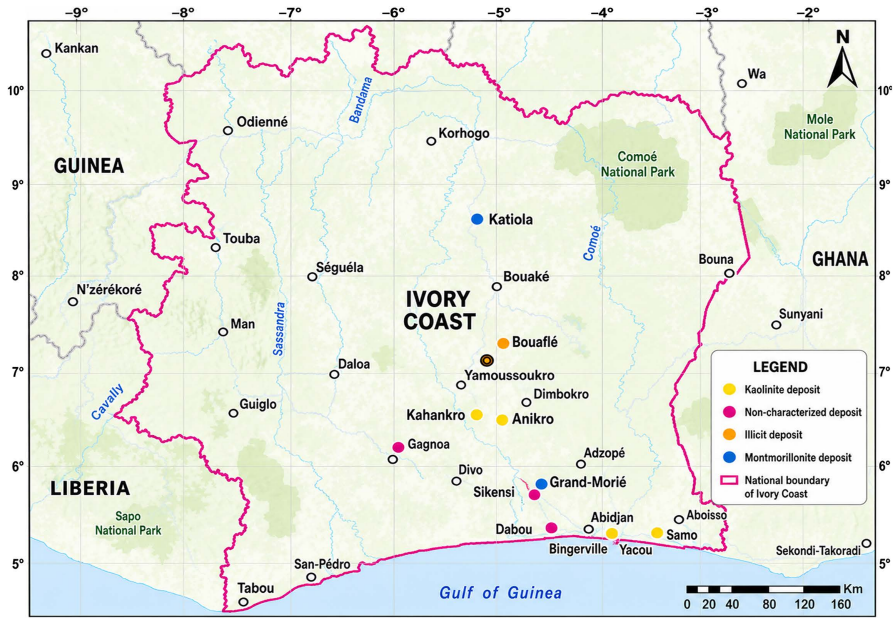

Figure 3. Spatial distribution of documented clay deposits.

3. Classification and Spatial Distribution of Ivorian Clays

3.1. Definitions and Classification Concepts

The word "clay" comes from the Latin argilla. It can designate a particular clay

mineral, a group of clay minerals, or a rock made mostly of such minerals. In the mineralogical sense, clay is a natural material consisting mainly of hydrated silicates or aluminosilicates with a layered crystal structure. In the textural sense, it is an earthy material of fine particles (equivalent diameter ≤ 2 μm) that becomes plastic with water and hardens on drying or firing [16]. The two definitions, mineralogical and textural, should not be confused when characterizing a deposit or interpreting its technological behavior.

3.2. Classification of Clay Minerals

Classifying clay minerals is not simple, because several criteria are involved [16]. They include the number of tetrahedral (T) and octahedral (O) sheets in the basic unit, the way the layers are stacked, the nature of the interlayer species and the chemical composition of the sheets. Three structural families cover nearly all clay minerals found in nature.

1:1 clay minerals (T-O structure) have one silica tetrahedral sheet covalently bonded to one aluminium (or magnesium) octahedral sheet. The layer is electrically neutral and holds no interlayer cations. Kaolinite [$Al_2Si_2O_5(OH)_4$] is the typical dioctahedral member. Its composition varies little, it hardly swells on hydration, and its cation exchange capacity is low (CEC: 3 - 15 meq/100 g).

2:1 clay minerals (T-O-T structure) have one octahedral sheet sandwiched between two tetrahedral sheets. The group is subdivided according to the interlayer region: pyrophyllite and talc have no interlayer sheet, illite contains non-exchangeable interlayer K^+ ions, and smectites (e.g., montmorillonite) hold exchangeable cations and water in an expandable interlayer, which gives variable basal spacings (d_{001} = 1.0 - 1.5 nm depending on hydration state) and a high CEC (80 - 120 meq/100 g). In 2:1:1 clay minerals (T-O-T-O structure), an extra hydroxide octahedral sheet (brucite or gibbsite type) is inserted between successive T-O-T units. Chlorite is the main representative of this group.

Table 1 gives the general structural classification of the clay mineral families recognized in mineralogical taxonomy [16], including species reported worldwide. Only a few of them have so far been confirmed by XRD in Ivorian deposits: kaolinite (1:1 group), illite/muscovite (2:1 mica-illite group) and montmorillonite (2:1 smectite group). These are the three families treated in Sections 3.4-3.6 and 4.1-4.3, and they are marked with † in **Table 1**. The other families and species are listed for taxonomic completeness; to our knowledge they have not been reported in the Ivorian geological literature.

3.3. Geological and Spatial Mapping of Clay Deposits

Geological mapping of the clay formations of Côte d'Ivoire is a prerequisite for judging their industrial potential. Clay types are found throughout the country, and their mineral assemblages and physicochemical properties change markedly with parent lithology, degree of weathering and local geomorphology. In the low-lying south, soils are thick and contain mottled clay horizons, a sign of poor deep

drainage. In the humid forest zone of the center-west and west, intense lateritization produces deep kaolinitic profiles. In the sub-Sahelian north, smectitic clays are found more often in valley bottoms and lacustrine settings.

The spatial distribution of documented clay deposits is presented in Table 2.

Table 1. General classification of clay mineral families (structural taxonomy after [16]).

Sheet type	Group	Octahedral character	Representative species
1:1	Kaolinite	Dioctahedral	Kaolinite, dickite, nacrite, halloysite
1:1	Serpentine	Trioctahedral	Antigorite, chrysotile, lizardite, berthierine
2:1	Pyrophyllite-Talc	Di/Trioctahedral	Pyrophyllite, talc
2:1	Mica-Illite	Dioctahedral	Muscovite, illite, glauconite
2:1	Smectite	Dioctahedral	Montmorillonite, beidellite, nontronite †
2:1	Smectite	Trioctahedral	Saponite, stevensite
2:1	Vermiculite	Trioctahedral	Vermiculite
2:1 fibrous	Sepiolite-Palygorskite	Trioctahedral	Sepiolite, palygorskite (attapulgite)
2:1:1	Chlorite	Di/Trioctahedral	Clinochlore, chamosite, donbassite, cookeite

Table 2. Distribution of clay deposits in Côte d'Ivoire and their documented applications.

Region/District	Locality	Principal clay type	Geographic coordinates	Documented applications	Reference (s)	Year
Lagunes (Ponts)	Dabou	Kaolinite	5˚19'70"N, 4˚22'80"W	Mortar; stabilized bricks	[13]	2008
Lagunes (Ponts)	Yaou	Kaolinite	5˚15'013"N, 3˚37'485"W	Bioplastic reinforcement	[17] [18]	2019-2024
Lagunes (Ponts)	Bingerville	Kaolinite	5˚18'N, 3˚50'W	Pollutant adsorption; geophagy	[19] [20]	2020; 2017
Lagunes (Ponts)	Samo	Kaolinite	5˚17'28"N, 3˚30'53"W	Road construction	[21]	2023
Lagunes (Ponts)	Anyama	Kaolinite (1:1)	5˚30'N, 4˚02'W	Pollutant removal from agro-industrial effluents	[22]	2021
Agnéby-Tiassa	Grand-Morié	Kaolinite	5˚59'N, 4˚08'W	Pollutant adsorption	[20]	2017
Hambol	Katiola	Montmorillonite (smectite)	8˚08.945'N, 5˚05.959'W; 8˚14.709'N, 5˚06.505'W	Characterization; pharmaceutical/geophagy; CEB production; pollutant removal	[14] [23]	2012; 2017
Marahoué	Bouaflé	Illite (green clay)	6˚59'N, 5˚45'W	Adsorption of methylene blue and cadmium	[19]	2020

Continued

Marahoué	Zuénoula	Kaolinite	7.424˚N, 6.052˚W	Electrochemical pollutant detection	[24]	2023
Bélier (Toumodi)	Kahankro/Anikro	Kaolinite	UTM: 263 - 271 km E; 729 - 731 km N	Soil fertility; agriculture	[15]	2014
Sud-Comoé	Gounioubé	Kaolinite (low crystallinity)	N/A	Mineralogical characterization; bleaching	[25]	2017
Gôh/Worodougou (Man)	Man	Kaolinite (calcined)	N/A	Natural pozzolan for clinker substitution	[26]	2022
Gôh	Gagnoa	Kaolinite	6˚07'37.6"N, 5˚56'15.0"W	Eco-construction; brick production	[10]	2022
Lagunes (Sikensi)	Sikensi	Kaolinite	5˚38'26.88"N	Construction	[26]	2022
Centre (Bocanda)	Bocanda	Kaolinite/Illite/Smectite	N/A	Pharmaceutical; antibacterial; gastrointestinal	[27] [28]	2012; 2014

CEB = Compressed Earth Brick; N/A = geographic coordinates not reported in the cited study.

3.4. Kaolinite Deposits

Kaolinite is the dominant clay mineral over most of the Ivorian territory. It forms mainly through the extensive diagenesis of feldspars under humid tropical conditions: high temperature, abundant rainfall and acidic soil pH [29]. Along the coastal sedimentary fringe, kaolinite is described as a detrital mineral concentrated in the marginal zones of the sedimentary basins, with little compositional variation [30]. Inland, kaolinite deposits linked to lateritic profiles build thick residual accumulations on Precambrian basement rocks.

Sagou *et al.* [25] studied the structural order of kaolin from the Gounioubé deposit by electron paramagnetic resonance (EPR) spectroscopy. They examined the iron status before and after citrate bicarbonate dithionite (CBD) bleaching and found structural defects in the form of short- and long-range disorder. This supports the idea that tropical kaolinites have low crystallinity. The point matters in practice, since the crystallinity index directly affects how reactive a kaolin is when heated, which is relevant for ceramic and geopolymer applications.

3.5. Smectite Deposits

Smectitic clays, mostly montmorillonite, have been found mainly in the Hambol region around Katiola, in the northern savannah belt of Côte d'Ivoire. They form from the weathering of basic parent rocks (basalts, amphibolites) in poorly drained valley-bottom positions, where the silica and magnesium released by hydrolysis are retained. Kpangni *et al.* [14] characterized Katiola montmorillonite with high-resolution N_2 gas adsorption. They reported high specific surface areas and marked energetic heterogeneity of the surface, in line with a strong capacity to adsorb pollutants.

3.6. Illite Deposits

Illite forms when muscovite progressively loses its interlayer potassium during moderate chemical weathering. It is therefore an intermediate product between primary micas and fully hydrolysed kaolinite [15]. Illite-bearing clays have been documented mainly around Bouaflé (Marahoué region) and in some deposits of the Bélier zone. On X-ray diffractograms, illite shows reflections at d = 10 Å (001), 5 Å (002) and 3.35 Å (003) that do not change after ethylene glycol solvation or heating at 550˚C. This is what separates illite clearly from smectite and kaolinite in routine diffractometric analysis [31].

4. Mineralogy and Physicochemical Properties

Ivorian clays consist mostly of kaolinite, illite and smectites (chiefly montmorillonite), together with non-clay phases such as quartz, goethite and hematite. This assemblage reflects the intensity of tropical weathering of silicate parent rocks in a hot, humid climate, and it controls almost every technological property that matters for industrial valorization. Unless stated otherwise, the structural and physicochemical parameters given in Sections 4.1-4.5 (CEC ranges, specific surface area, plasticity indices) are generic values for each mineral family from the broader mineralogical literature [3] [16]. They were not measured on Ivorian samples and serve only as a reference framework for interpreting the family-level behavior of local deposits. Where a property was measured directly on an Ivorian sample, we attribute it to the corresponding study (for example the Katiola and Bingerville data discussed in Sections 3.4-3.5 and 5.2).

4.1. Kaolinite: Structure and Properties

Kaolinite [$Al_2Si_2O_5(OH)_4$] is a 1:1 dioctahedral clay mineral: a silica tetrahedral sheet is joined to an alumina octahedral sheet through shared apical oxygen atoms. The resulting layer is electrically neutral, so the interlayer cannot expand significantly, which gives the mineral excellent dimensional stability. Its CEC is low (3 - 15 meq/100g) and comes mainly from broken bonds at crystal edges and from isomorphous substitutions. Because it is chemically and thermally stable, kaolinite is well suited to ceramics, refractory bricks and roofing tiles, which are typically fired between 900˚C and 1200˚C. When kaolinite is dehydroxylated at about 500˚C - 700˚C it turns into metakaolin, a highly reactive amorphous aluminosilicate with marked pozzolanic activity that is also useful for geopolymer synthesis.

4.2. Smectites: Structure and Properties

Smectites, and montmorillonite [$(Na, Ca)_{0.3}(Al, Mg)_2Si_4O_{10}(OH)_2{\cdot}nH_2O$] in particular, are expandable 2:1 clay minerals. Their interlayer space holds exchangeable cations (Na^+, Ca^{2+}, Mg^{2+}) and a variable amount of water, so basal spacings range from about 10 Å when collapsed to 15 Å or more when fully hydrated. This expandability gives a very high CEC (typically 80 - 120 meq/100 g) and a large

specific surface area (400 - 800 $m^2 g^{-1}$), which explains why smectitic clays adsorb heavy metals, organic dyes and pharmaceutical compounds so well. The same properties make these clays highly plastic and prone to swelling. This can be a problem in civil engineering but is an advantage in drilling muds and pharmaceutical encapsulation.

4.3. Illite: Structure and Properties

Illite is a non-expandable 2:1 clay mineral. Interlayer K^+ ions bind the T-O-T layers electrostatically and prevent significant swelling. Its CEC (10 - 40 meq/100 g) and specific surface area fall between those of kaolinite and smectites. Illite adds to soil cohesion and plays a part in potassium cycling in weathering environments. Its moderate mechanical and adsorptive properties make it useful in brick production and as a complementary adsorbent for moderately charged pollutants.

4.4. Associated Non-Clay Minerals

Quartz is the commonest non-clay mineral in Ivorian clay deposits. It raises compressive strength and lowers plasticity, which improves the dimensional stability of fired ceramics. Being poorly reactive, it contributes almost nothing to adsorption. Iron oxides and hydroxides, mainly goethite (α-FeOOH) and hematite (α-Fe_2O_3), give tropical clays their red-to-brown color. Besides this visual effect, iron minerals take part in adsorption and catalytic reactions, notably in heterogeneous Fenton-type AOPs, where structural Fe^{3+}/Fe^{2+} redox couples generate hydroxyl radicals.

4.5. Key Physicochemical Parameters

Grain-size distribution controls specific surface area and overall reactivity. A high fraction of particles < 2 μm increases plasticity and adsorption capacity, whereas coarser silt and sand reduce cohesion and deformability. Plasticity, measured through the Atterberg limits (liquid limit, plastic limit, plasticity index), describes how well a material can be shaped. Smectites generally have high plasticity (PI > 30%), illites moderate plasticity (PI = 15% - 30%) and kaolinites moderate-to-low plasticity (PI = 10% - 20%). Plasticity is essential for making bricks and tiles, although too much of it can cause cracking during drying.

Cation exchange capacity reflects how well a clay can fix and exchange cations with the surrounding solution. It depends on crystal structure, specific surface area and pH. Smectites have the highest CEC, followed by illites and then kaolinites. A high CEC is especially important for heavy metal and dye adsorption, for nutrient retention in agronomic settings and for catalytic or pharmaceutical uses. Organic matter affects porosity, thermal stability and color. A moderate amount can improve water retention in agricultural soils, but too much changes firing behavior by creating extra porosity and discoloration. Getting the most out of Ivorian clays therefore calls for thorough characterization combining X-ray diffraction (XRD), X-ray fluorescence (XRF), Fourier-transform infrared spectroscopy

(FTIR), scanning electron microscopy (SEM), particle size analysis and CEC measurements.

5. Valorization Perspectives

Ivorian clays are diverse and abundant, and they open several valorization routes in construction, health, environmental remediation, advanced materials and the agri-food sector. The sections below review the applications documented so far, concentrating on quantitative performance data and on mechanistic interpretation.

5.1. Applications in the Construction Sector

5.1.1. Compressed Earth Bricks

Compressed earth bricks (CEBs) made with Katiola smectitic clay and shea cake residues were developed by Doubi *et al.* [23]. Adding up to 10 wt.% shea cake created controlled porosity, which lowered brick density and reduced thermal conductivity from 0.72 W m^{-1} K^{-1} (control) to 0.52 W m^{-1} K^{-1} (10% residue). Bulk density and thermal conductivity were strongly linearly correlated ($R^2 > 0.95$), which supports this pore-engineering approach for thermally insulating structural elements suited to tropical climates. Kouamé *et al.* [4] later took the idea further by adding soursop seed granules of different sizes. Coarser granule fractions gave better thermal insulation while keeping enough compressive strength for low-rise housing.

In the Lagunes region, Dabou clays were tested for stabilization with Portland cement (PC) as a hydraulic binder, in order to make compressed stabilized earth bricks (CSEBs) [13]. Cold stabilization with 5% - 10% PC clearly improved compressive strength and durability under wetting-drying cycles. This makes such bricks a sustainable, locally sourced alternative to fired bricks for low-cost housing. Kouakou *et al.* [10] also characterized two clay raw materials from Sikensi and Gagnoa for eco-construction. Their mineralogical compositions were compatible with brickmaking, and plasticity indices and mechanical performance were satisfactory after firing at 900˚C - 1000˚C.

5.1.2. Calcined Clays as Supplementary Cementitious Materials

Replacing Portland clinker with calcined natural clays is a high-impact way to cut the carbon footprint of the cement industry, which accounts for about 8% of global CO_2 emissions. Kouakou *et al.* (2022) evaluated two kaolinitic clays (ME1, ME2) from Man in western Côte d'Ivoire, calcined at 710˚C. ICP-AES analysis of the raw samples showed that SiO_2, Al_2O_3 and Fe_2O_3 together made up more than 70% of the oxides, meeting the minimum for pozzolanic materials set by ASTM C618. XRD confirmed kaolinite, quartz, goethite and hematite in the raw samples. After calcination the kaolinite and goethite peaks disappeared and an amorphous metakaolin phase formed. Laser diffraction showed multimodal size distributions in the raw samples (populations at 2, 10 and 39 μm) and coarser unimodal distributions after calcination, consistent with particle sintering. In the saturated lime

test, calcined samples consumed more than 80% of $Ca(OH)_2$ after 7 days, against about 48% for raw samples, which confirms strong pozzolanic reactivity. These results suggest that Ivorian kaolinitic clays calcined at moderate temperature could be used as LC3 (Limestone Calcined Clay Cement) components, lowering the clinker factor and the associated CO_2 emissions.

5.2. Applications in Health and Pharmacy

Clays have long been used in Côte d'Ivoire as medicines and cosmetics, and this use reflects empirical knowledge built up over generations. Kouakou *et al*. characterized Bocanda clays eaten by local people and showed that the presence of kaolinite, illite and smectite (montmorillonite) together explains their use as gastrointestinal protectants, antidiarrheal agents and antiseptic skin applications [27]. The three minerals complement each other: kaolinite adsorbs toxins and pathogens, montmorillonite brings a high specific surface area and smectogenic action, and illite adds structural cohesion and moderate antimicrobial activity [9].

Kouakou *et al*. [28] went on to quantify the antibacterial activity of Bocanda clays against several bacterial strains. Efficacy depended on both the mineralogical composition of the clay and the type of bacterium, which suggests that the mechanisms involved (possibly ionic release, surface pH modification and physical entrapment) are complex and specific to each clay. Coulibaly *et al*. studied Bingerville clays that the local population eats as geophagy. They reported high specific surface areas (26 - 43 $m^2\ g^{-1}$) and strong adsorption capacities. This supports the hypothesis that eating clay has a detoxifying effect by trapping toxins, pesticides, microorganisms and gases in the gastrointestinal tract, a practice that is now getting renewed scientific attention in the context of food safety [32].

5.3. Applications in Water Remediation

5.3.1. Clays as Adsorbents

Whether Ivorian clays can be valorized for water remediation depends heavily on their mineralogy, purity and surface properties. Kedi *et al*. showed that natural clays from Katiola (smectite-rich) and Anyama (kaolinite-rich) can effectively remove copper, zinc, lead, total phosphorus and total nitrogen from liquid waste of a sugar production unit [22]. Katiola clay consistently removed more pollutant than Anyama clay. This agrees with the generic CEC ranges for the two mineral families (2:1 smectitic/chloritic minerals: CEC > 80 meq/100 g; 1:1 kaolinite: CEC < 15 meq/100 g, Sections 4.1 and 4.2). It does not rest on site-specific CEC measurements, which Kedi *et al*. did not report for these two samples, so the explanation should be read as a family-level interpretation, consistent with the mechanistic framework of Gu *et al*. [7].

Coulibaly et al. studied the simultaneous adsorption of methylene blue (MB) and cadmium ions from aqueous solution on Bouaflé green clay, which is dominated by illite. Under optimized conditions removal exceeded 90% for MB and 80% for Cd^{2+}. This was related to the ability of silanol and aluminol groups on the illite surface to interact with cationic dyes and heavy metal ions by ion exchange

and surface complexation [19]. *Kouakou et al.* looked at the adsorption of methyl red, an anionic azo dye, on two Ivorian kaolinitic clays. Kinetics were pseudo-second-order and the isotherms were Langmuir-type, which points to monolayer chemisorption on a finite number of homogeneous active sites [21]. Méité *et al.* examined the photocatalytic role of kaolinite in the degradation of methylene blue by the photo-Fenton process. Clay-mediated heterogeneous catalysis enhanced hydroxyl radical generation and pollutant mineralization under UV-visible irradiation [18].

5.3.2. Clays as Catalysts in Advanced Oxidation Processes

Advanced oxidation processes (AOPs) based on clay catalysts are an emerging and promising way to treat water contaminated with recalcitrant organic micropollutants, endocrine disruptors and pharmaceutical residues [33]. Ivorian clays modified by intercalating iron, aluminum, titanium or copper cations gain catalytic properties from a larger interlayer spacing and surface area, from Lewis acid sites, and from the ability to cycle between reduced and oxidized metal states. Pillared interlayered clays (PILCs) are particularly effective in heterogeneous Fenton reactions, in which structural Fe^{2+}/Fe^{3+} couples promote the *in situ* generation of hydroxyl radicals (·OH) that mineralize dissolved organic contaminants non-selectively. Pohan *et al.* showed photocatalytic and antimicrobial activity for [Ag-TiO_2]:[clay] nanocomposites prepared with different clay ratios, which confirms that Ivorian clay matrices can support photoactive nanoparticles in visible-light-driven AOP systems [8]. Depositing noble and transition metal nanoparticles on clay surfaces improves catalytic efficiency further, and this opens the way to low-cost, regenerable water treatment catalysts made from local raw materials.

5.4. Applications in Bioplastics and Advanced Materials

Biobased, biodegradable composites are a strategic response to plastic pollution. Meite *et al.* carried out a systematic study of cassava starch bioplastic films reinforced with raw kaolinite and with metakaolin (kaolinite calcined at 700˚C) from the Yaou clay deposit [11] [18] [34]. In thermomechanical tests, films with 10 wt.% metakaolin outperformed their kaolinite-reinforced equivalents, reaching a maximum tensile stress of 7.4 ± 0.4 MPa and a Young's modulus of 77.2 ± 0.6 MPa. Water vapor permeability fell and biodegradation was better controlled. These gains were attributed to the high aspect ratio and chemical reactivity of metakaolin platelets, which interact strongly with starch macromolecules (amylose and amylopectin) through hydrogen bonding and possibly covalent cross-linking. This limits chain mobility and reduces the free volume available for moisture diffusion. Meite *et al.* later extended the approach to ternary composites with coconut fiber and/or metakaolin, which showed synergistic reinforcement and even better hydrophobicity [18]. Together, these results make thermally activated Ivorian kaolinitic clays viable, moderate-cost fillers for a sustainable bioplastics industry, with possible uses in food packaging and agricultural mulching films.

5.5. Traditional and Artisanal Valorization

Outside the laboratory, Ivorian clays also sustain important traditional economic activities. The pottery of the Mangoro women potters in the Katiola area is ancestral material knowledge handed down through generations: smectitic clays are shaped into functional objects (jars, pitchers, cooking vessels) and decorative ceramics. Clay therapy and cosmetics rely on local resources as well. Naturopathic practitioners prepare clay-based remedies combined with medicinal plants, and white and red clays are sold commercially in cosmetic preparations for their purifying, soothing and sebum-absorbing effects. These traditional uses are an important source of income for rural communities and a base on which modern scientific valorization can build.

6. Technical, Economic, and Regulatory Constraints

Ivorian clays have considerable scientific and economic potential, but industrial valorization runs into a set of overlapping technical, geological, logistical and regulatory constraints. For now they restrict exploitation to small-scale artisanal or research-stage activity.

Geological variability is the most basic difficulty. Clay deposits in Côte d'Ivoire differ markedly in mineralogical composition, impurity content and physicochemical properties, even within a single geographic unit. This reflects both the complexity of tropical weathering and the diversity of parent lithologies. It makes quality standardization difficult and technological performance harder to predict for industrial users. A deposit that looks promising in surface samples may turn out to be heterogeneous at depth, and systematic borehole investigations, which are still rare in the literature, would be needed to find out [4].

The lack of a harmonized national inventory is a second major constraint. SODEMI exploration campaigns and isolated academic studies have identified many deposits, yet there is no comprehensive, georeferenced and publicly accessible database that brings together mineralogical, physicochemical and reserve data for Ivorian clay occurrences. This scattering of data raises prospecting costs, makes strategic planning harder for investors and complicates comparison between regions. The variety of analytical protocols used by different teams reduces comparability across studies even further.

At the processing stage, technical constraints include little beneficiation infrastructure for removing the iron oxide impurities that affect the whiteness and firing behavior of ceramics, no standardized drying and firing protocols adapted to local clay compositions, and insufficient control of the calcination conditions needed to maximize the pozzolanic reactivity of metakaolin [5]. The raw material itself may need washing, selective flocculation or magnetic separation to meet industrial specifications, and these operations require capital investment that most local operators cannot afford.

Logistical constraints include poor roads in some deposit-bearing regions, limited access to reliable energy for industrial drying and firing, and a lack of local

testing laboratories with the instruments (XRD, XRF, BET surface area analyzer) needed for systematic quality control. On the regulatory side, mining rights frameworks are unclear or overlap, artisanal mining permits are cumbersome to obtain, and environmental protection measures for extraction are weakly enforced.

Finally, imported industrial clays are hard competition, especially high-purity kaolin from Brazil and China used in paper coating, pharmaceuticals and high-performance ceramics. Without prior beneficiation, Ivorian clays have limited access to these premium-value segments. Overcoming the constraints above will take coordinated action at scientific, industrial, institutional and policy levels.

7. Practical Recommendations and Research Priorities

A sustainable valorization of Ivorian clays calls for an integrated national strategy resting on the following complementary pillars:

1) Systematic national mapping and characterization: A multi-institution program should map clay deposits at the 1:200,000 scale, combining remote sensing (hyperspectral imaging, Sentinel-2 clay mineral indices), field sampling and laboratory characterization with standardized XRD, XRF, FTIR, BET and CEC protocols. Drilling at selected priority deposits should establish reserve geometry and subsurface variability. All results should go into a georeferenced, publicly accessible national clay database.

2) Establishment of a national reference sample bank: A curated physical and digital repository of reference samples from characterized deposits should be set up. It would allow comparisons between laboratories, quality certification, and faster screening by industrial users and researchers.

3) Standardization of technological suitability criteria: Quality standards specific to each sector (ceramic, construction, pharmaceutical and adsorbent grades) should be drawn up together with industrial partners and regulators, building on international norms (ISO, ASTM, EN) adapted to the Ivorian geological context.

4) Development of pilot-scale valorization projects: Pilot units should be established, in partnership with industry, development agencies and municipal water utilities, for calcined-clay supplementary cementitious materials (LC3 concept), compressed earth brick manufacturing and clay-based water treatment systems. They would act as demonstrators, knowledge-transfer platforms and training sites.

5) Capacity building and knowledge transfer: University-industry partnerships should be formalized to train engineers and technicians in clay mineralogy, ceramic science and environmental applications. Postgraduate programs on clay valorization deserve support through competitive national funding, and results should be disseminated systematically in peer-reviewed journals indexed in Scopus and Web of Science.

6) Integration of sustainability and circular economy principles: Life cycle

assessment (LCA) should be applied to every proposed valorization route to quantify its environmental gains compared with imported or conventional alternatives. Routes that use industrial by-products (shea cake residues, coconut fiber, agricultural wastes) as co-constituents of clay-based materials should be given priority, in line with circular economy and ecological transition goals.

8. Conclusions

This review shows how strategically important Ivorian clays are, scientifically and economically. The geological diversity of Côte d'Ivoire has produced deposits of remarkable mineralogical richness, dominated by kaolinite, illite and smectites together with quartz and iron oxides. This mineralogical heterogeneity is not only a limitation. It is also a versatility that allows several valorization sectors to develop at once: eco-construction and sustainable materials, water remediation, pharmaceutical and cosmetic applications, advanced oxidation catalysis and biobased composites.

The evidence reviewed indicates that Ivorian clays perform comparably to clays already exploited industrially elsewhere in Africa and the world. Smectitic (Katiola/Hambol) and kaolinitic (Bingerville) clays have adsorption-related surface properties that are generally lower than those of high-purity commercial bentonites. The measured specific surface area of Bingerville kaolinitic clay (26 - 43 $m^2 g^{-1}$, Section 5.2), for instance, is well below the generic range reported for smectites as a family (Section 4.2). Even so, these clays remain good enough for effective pollutant removal, as shown experimentally in Section 5.3. Kaolinitic deposits from the Lagunes, Gôh and Marahoué regions show pozzolanic reactivity after calcination that qualifies them as LC3 cement components. Metakaolin from Yaou kaolinite markedly improves the mechanical and barrier properties of cassava starch bioplastics, which validates a fully local and renewable valorization chain.

Moving from research-stage demonstrations to sustained industrial exploitation will nevertheless require concerted action on the structural constraints identified here: the lack of a systematic national inventory, the geological variability of deposits, scattered data, missing beneficiation infrastructure and regulatory uncertainty. The integrated strategy proposed in this review, which combines systematic mapping, a reference sample bank, protocol standardization, pilot projects, capacity building and sustainability assessment, offers a coherent operational framework for tackling these obstacles.

In conclusion, Ivorian clays are a major opportunity for industrial diversification, ecological transition and socio-economic development. Rational exploitation, backed by sustained research, public-private investment, regulatory clarity and technological innovation, could strengthen the country's autonomy in strategic mineral resources and contribute to national sustainable development objectives.

Data Availability

No new primary data were generated or analyzed for this review. All data dis-

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Declaration of AI-Assisted Technology Use

During the preparation of this manuscript, the authors made extensive use of AI-assisted tools, specifically large language models, to support literature synthesis, drafting, translation, and language editing. While this assistance was substantial, the scope, source selection, interpretation, and conclusions of the review remained under the authors' direction. All AI-generated content was critically reviewed, verified against the original sources, and approved by the authors, who take full responsibility for the accuracy, integrity, and originality of the final manuscript.

Author Contributions

Namory Méité: Conceptualization, methodology; software; validation; writing-review and editing, **Alfred Niamien Kouamé:** formal analysis; investigation, resources **Nina Lydie Amon:** data curation; writing-original draft preparation**, Ali Sanou**: writing-review and editing, **Leygnima Yaya Ouattara**: formal analysis; investigation, resources**, Bi Irié Hervé Goure Doubi:** writing-review and editing; visualization; supervision; project administration; funding acquisition, **Lébé Prisca Marie-Sandrine Kouakou:** writing-review and editing; visualization; supervision; project administration; funding acquisition, **Léon Koffi Konan:** supervision; project administration; funding acquisition. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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