



Environmental impacts of thermally activated clays for low carbon cement production

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ABSTRACT

The environmental impacts of activated clay produced using a wide range of clay mineralogy (with varying carbonate content), fuels (including alternative fuels), and thermal activation technologies were assessed using the life cycle assessment methodology. Global warming potential (GWP) values for thermally activated clays produced using the four different technologies and six fuel use scenarios ranged from 186 to 360 kg CO₂-eq. per tonne of activated clay. Depending on the fuel type, thermally activated clay can have a non-biogenic GWP of 103–360 kg CO₂ eq. per tonne, biogenic GWP of 29–94 kg CO₂ eq. per tonne. Changing the fuel type can decrease GWP by up to 30% (both biogenic and non-biogenic) and 43% (only non-biogenic), whereas changing technology can decrease GWP by up to 28%. The variability in the GWP of LC3 containing 50%, 35%, and 25% Portland clinker was assessed, where activated clay contributed 6–14%, 9–22% and 14%–30% of the GWP, respectively.

1. Introduction

Concrete is an important infrastructure material. Owing to the increasing demand for infrastructure and 5–8% of global CO₂ emissions arising from cement production, a vital concrete component, there is a global need for low carbon cement [1]. One strategy to reduce the carbon footprint of cement is substituting clinker with supplementary cementitious materials (SCMs) [2,3]. Commonly used SCMs include coal fly ash and ground granulated blast furnace slag (GGBS) due to their suitable chemical compositions, availability, and ease of processing [4]. However, their availabilities may change in the future because of transitions to renewable electricity generation and steel production via electric arc furnaces [5]. Activated clays are a viable alternative to these SCMs. As they are abundant and suitable for co-substitution with limestone to form limestone calcined clay cements (LC3) with clinker factors of 0.5 or lower [6–8]. There is also substantial potential for activated clays to be produced using low-grade clay deposits, mixed clay types, overburden or excavated soil, and laterite which are readily accessible

and cheap [9–12].

Thermal and mechanochemical activation are promising methods for activating clays to form reactive SCMs [13–16]. Thermal activation is the more mature technology that has proven cost-effectiveness and scalability [17]. Rotary and flash calcination are two thermal activation methods that have gained popularity in recent years as they offer good process control in terms of time and temperature and achieve uniform products [18]. Thermal activation involves heating clays to a specific temperature range to (partly) decompose their molecular structure and enhance their pozzolanic reactivity [19]. Here, transformations such as dehydration and dehydroxylation occur. Dehydration involves the removal of pore water and adsorbed water present within clay minerals [20]. Dehydroxylation decomposes clay molecules into poorly crystalline structures that are pozzolanic and reactive with fine limestone [21–23].

The temperature range for the thermal activation of clay minerals varies depending on the type of clay, intended application, and production scale. Thermal activation temperatures in the laboratory are

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typically 400–600 °C for kaolinite, 400–700 °C for illite, and 600–800 °C for montmorillonite [13,14,24]. These temperature ranges correspond to that at which significant changes occur in the structures and dihydroxylation (after structural decomposition) of these clays [24,25]. It was reported that the optimal temperature range for industrial calcination of kaolinite clay is 700–850 °C [13,26]. The mineralogical composition and crystallinity of the clay, crystallinity, and optimal calcination temperature, critically influence the extent of activation and quality of the resulting SCM [27]. Flash calciners and rotary kilns can be used to heat clays to the required temperatures to transform them into a reactive material. These technologies have their own operational characteristics as listed in Table 1.

Regardless of the thermal technology employed for a particular type of clay, the activated clays exhibit similar properties when activated at the same temperature [29,30]. Agglomeration of activated clays post thermal treatment is common in rotary calcination which can be mitigated through further grinding [13,29,31]. The choice between rotary and flash calcination depends on specific requirements such as characteristics of the raw clay, suitability of existing kilns and plant equipment to be repurposed or retrofitted, etc. [18,32]. The equipment used is related to the technology adopted and the energy utilised varies in each type.

There are several case studies on the industrial-scale production of thermally activated clays using existing rotary calciners [17,26,31,33,34], but there is limited information regarding their environmental impacts. Relatively few studies have assessed the environmental impacts of thermally activated clay production using life cycle assessment based on industrial scale primary data [35,36]. Few studies have also attempted to assess direct emissions from fuels used during thermal activation [31,37,38,39]. Some studies have attempted to use the reported industrial and lab scale thermal activation energies to calculate the impacts associated with LC3 production [40–46]. However, the influence of activation technology and corresponding changes in fuels used on the climate change impact of thermally activated clay remains unclear. Existing studies have not considered the influence of clay mineralogy on the performance of thermal activation methods and associated environmental impacts.

This study aims to examine the environmental impacts of industrially produced activated clays using different thermal activation technologies such as flash, rotary single-body (conventional existing and retrofitted), and rotary double-body, focusing on climate change and cumulative energy demand (CED) impacts. We compile and provide industrial scale data from different sources to enable this analysis. We also assess the effects of carbonate content and fuel type including waste-derived alternative fuels on the environmental impacts of thermally activated clays. The climate change impacts of thermally activated clay and LC3

cements are compared with other commonly used SCMs, blended cements, and CEM I. This study aims to serve as a benchmark to compare the impacts of existing, emerging, and future clay activation technologies, and for calculation of the impacts associated with cement, concrete, and infrastructure value chains that use activated clays.

2. Methodology

2.1. Materials

Mineralogical composition of 70 UK clays were used to inform the carbonate content analysis here since they cover a wide range of low-grade mixed clays [47]. The clays contained an average of 40 wt% kaolinite, while total clay content varied significantly, ranging from 10 to 82 wt%, and carbonate mineral content ranged from 0 to 50 wt%. The complete list of clays and their compositions are provided elsewhere [47,48]. Carbonates (notably CaCO_3 , MgCO_3 , and $\text{CaMg}(\text{CO}_3)_2$), present in the clay during thermal activation are converted to CaO and MgO (present as free or reacted forms) by releasing CO_2 (direct emissions). If >5 wt% of carbonates are present in the raw clay, the amount of free lime in LC3 may exceed the allowable limits specified in standards [49,50]. Based on these limits, 5 wt% carbonates was considered as the maximum amount for the clays to be compliant (including LC3–50, LC3–35, and LC3–25), and the corresponding average CO_2 emissions for these clays were assessed and used in the study. In the case of LC3 production, one of the 70 UK clay samples was used in the LCA model because of the specific property of raw clay (>40% kaolinite content) and corresponding thermally activated clay (moderately reactive with R3 value of 448 J/g). The properties of this raw and activated clay sample are presented in Supplementary Material S1 (Section S1).

2.2. Description of thermal activated processes

Thermal activation of clays for SCM production broadly involves five steps: i) clay extraction (quarrying) and preparation, which may include homogenisation and cleaning, ii) transportation of extracted clay to the activation or cement plant, iii) pre-processing of clay which involves grinding and drying, iv) thermal activation i.e., calcination, with or without colour control, and v) post-processing, possibly involving grinding of the activated clay.

2.2.1. Thermal activation through rotary kilns

Existing conventional rotary kilns (single-body) used for clinker production can be used as such or retrofitted to thermally activate clay [28,34,37]. Additionally, rotary double-body kilns, which have two longitudinal parts with different diameters, can also be used. A cylindrical rotary kiln usually measures 20–40 m in length and 3–6 m in diameter, positioned at a slight downward angle. The temperature control in a rotary kiln is achieved by precisely adjusting the heating elements and the rotation speed [34].

In conventional existing and retrofitted rotary kilns, there is a cylindrical rotary body, a cooler, and a preheating system such as cylindrical cyclones for dry kiln systems [51,52]. In a wet existing kiln, drying occurs in the first part of the kiln which acts as a rotary dryer. The material residence time in a rotary kiln is relatively long, ranging from several minutes to a few hours, depending on the material and its desired properties. In a rotary double-body kiln, the first shaft allows drying, chemically bound water is removed in the second shaft, and rapid cooling for colour control can be subsequently attached. The total activation time in a rotary double-body kiln is typically 18–30 min including colour control. It has been reported that rotary double-body kilns can be more efficient than single-body rotary kilns [53].

Clay feedstock is reduced to the required size (typically ≤ 2 mm) using a vertical mill or similar equipment, in the calcination unit or cement plant. Fuel is injected at the lower end of the kiln and the combusted hot gases pass through the length of the kiln and if present

Table 1

Comparison between rotary and flash calcination technologies [13,18,28]. Characteristics that are present and absent are marked with ticks (✓) and crosses (×), respectively.

	Rotary kiln	Flash calciner
Uniform temperature throughout calcination zone	×	✓
Accepts a wide range of feed (size and moisture)	✓	×
Activation of irregular shaped particles	✓	×
Control over temperature and residence time	×	✓
Requires grinding before calcination	×	✓
Requires grinding after calcination	✓	×
Quick start	×	✓
Colour control	✓	✓
Use of waste heat from finished product	×	✓
Can handle any type of clay	✓	×
Requires additional equipment for preprocessing - low processing costs	×	✓
Requires flame stabilisation and control	✓	×
Short residence time	×	✓

into the preheating system. Activated clay exits from the lower end of the kiln and moves into the cooler. In the cooler, the colour change of the clay is initiated with an additional injection of fuel; cooling occurs by passing the clay over a rapid counterflow of air. A flowchart summarising the thermal activation of clay in rotary kilns is shown in Supplementary Material S1 (Section S2).

2.2.2. Thermal activation through flash calciners

Flash calcination is a relatively new technology designed to rapidly heat fine particles in a high-velocity hot gas stream [27,54,55]. Temperature control in a flash calciner is achieved by adjusting the temperature and flow rate of the hot gas stream through the reactor [18]. Flash calcination allows for complete calcination while preventing formation of inert phases at high temperatures [56]. The material residence time in a flash calciner is relatively short compared to rotary, typically a few seconds, and the total activation process takes a couple of minutes including colour control [13,54]. The efficiency of flash calcination is influenced by several factors: the particle size distribution of the clay; and the specific conditions within the calciner, such as temperature, retention time, and atmospheric conditions [18,55,57].

The flash calciner system consists of multiple preheating cyclones, a cylindrical calciner vessel, a colour control reactor and a series of cooling cyclones. Feedstock with the required fineness and moisture is introduced at the top preheater cyclone and then carried through the preheating stages before reaching the calciner [58]. Fuel is injected directly into the calciner, and the conversion process is completed in a few seconds. The hot air from the calciner is passed (recuperated) into the dryer upstream. After calcination, activated clay is passed through the colour control reactor, where additional fuel is injected in small quantities (when compared to the calciner fuel) to secure a reduction zone during the first stage of cooling. Then the activated clay is passed through two additional cooling cyclones. Finally, a forced draught fan pushes fresh air into the bottom cyclone, which is used to cool the

activated clay to its final temperature. The heated air rising from the bottom cyclone stages is recirculated back into the calciner as secondary air, securing heat recuperation and helping control the gas flow rate in the whole system. A flowchart summarising the thermal activation of clay in a flash calciner is shown in Supplementary Material S1 (Section S3).

2.3. Life cycle assessment

2.3.1. Goal and scope

The goal of this study is to compare the environmental impacts of thermally activated clay produced using four technologies – rotary kilns (conventional existing, retrofitted, and double-body) and flash calciner – and limestone calcined clay cements (LC3-50, LC3-35, and LC3-25) produced using the thermally activated clay, at an activated clay to limestone ratio of 2:1. Two functional units are used: (i) 1 kg activated clay, which implies that the activated clays studied here have the same technical performance, e.g., reactivity; and (ii) 1 kg cement, used for comparing LC3 with Portland cements (PCs). The compositions of the LC3 and PCs considered are given in Table S2 and S3 of Supplementary Material S1, Section S4.

Clay can be sourced from quarries as the primary material or as a by-product, e.g., overburden, from quarries or excavation sites during construction. Sourcing clay as the primary product from a quarry pit near to cement plant at distance of 20 km was considered here. A cradle-to-gate system boundary (Fig. 1) including clay extraction and transportation, and processes in the activation unit such as pre/post-processing was used. Thermal activation (Calcination) in an integrated cement plant was considered where the activated clay produced with the required fineness was blended in the final stage of cement production. For production of cement such as CEM I and LC3 in an integrated plant, a cradle-to-gate system (Fig. 1) including the extraction and transportation of fuels and raw materials for clinker were included. The

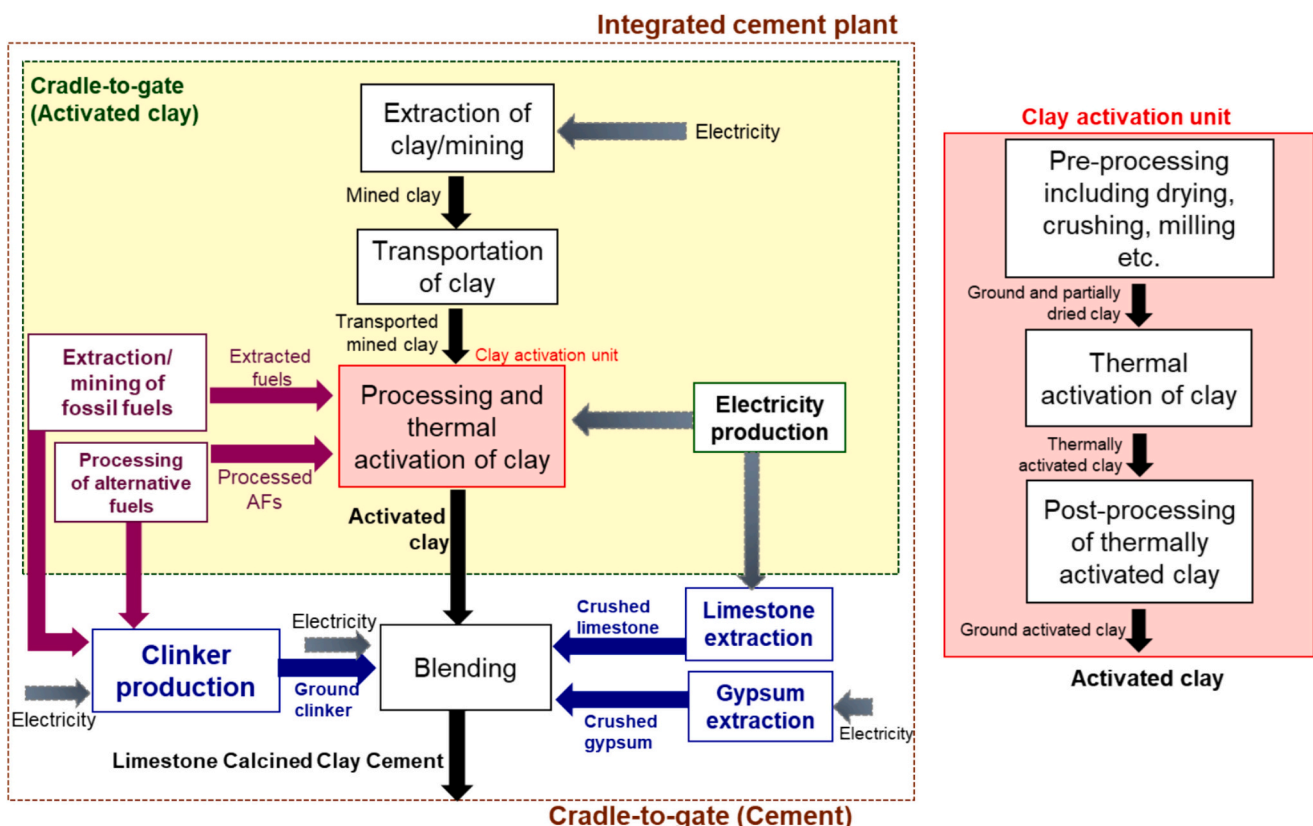


Fig. 1. Flowchart indicating the product system modelled.

activated clays produced using the different thermal activation technologies were assumed to exhibit comparable properties and characteristics such as reactivity [30]. Other SCMs, such as GGBS and fly ash, were assumed to be burden free at their points of generation, consistent with the ecoinvent cut-off system model. Environmental impacts due to processing of materials from their points of generation to their use as SCMs were included.

Life cycle impact assessment was carried out using the IPCC (2021) and cumulative energy demand (CED) methods. The indicators for these methods are GWP, 100 years (kg CO₂ eq.) and energy consumed (MJ eq.) respectively. Also, the ReCiPe 2016 method was used to calculate other environmental impacts. The geographical scope used was a generic European location (Europe without Switzerland), which defined the electricity mix. Our decision to focus on Europe is based on good data availability for this region and our aim to maintain a generic scope as the thermal activation technologies considered in this study can be adopted worldwide.

2.3.2. Inventory

Activity Browser (v2.9) was used for LCA modelling, and the ecoinvent database (v3.9.1 cut-off system) was used to model upstream and background activities, such as material extraction and transportation, electricity production, and transportation of fuels for the production of thermally activated clays and cements. Primary data related to the production of activated clays were obtained from industrial scale processes. These processes include those related to the clay activation unit (as shown in Fig. 1) such as pre/post-processing, activation of clay, and the electricity consumed. Upstream data associated with the construction of the thermal activation facility (plant and equipment) and related processes were excluded. The specific inventory dataset used for each input processes related to thermal activation are given in Table S4 of Supplementary Material S1 (Section S4).

The data pertaining to the production CEM I and blended PCs were considered from the ecoinvent database, while LC3s were modelled specifically for this study. The existing European dataset related to the CEM I and other blended PCs were considered. For LC3 production, the electricity for final clinker grinding was modified considering the reduced amount of clinker as mentioned in Table S3 of Supplementary Material S1 (Section S4). For inputs related to LC3, the European dataset was used when available and are listed in Table S2 of Supplementary Material S1 (Section S4).

2.3.2.1. Mass loss of raw clays during activation. Thermal activation of clay causes significant mass loss from the presence of free and chemically bound water (dehydration and dehydroxylation of clay minerals), and decomposition of organic matter and carbonates. The mass loss caused by dehydration and dehydroxylation varies depending on the type of clay, including kaolinite, montmorillonite, illite, and mixed types [59,60]. Mass losses owing to the presence of free moisture vary depending on the clay source. For instance, Dhandapani et al. (2023) [12] reported clay moisture contents before activation of 20–40% depending on source and storage/transport conditions. Processing parameters such as temperature and residence time also influences the extent of mass loss [54,56,61].

The total mass loss during thermal activation is a critical parameter for assessing the efficiency of the activation process since it affects the input mass of clay required to achieve the desired output. The primary data used here, which are for industrial scale production of thermally activated clay, show an average moisture content of ~20 wt% in the raw clay and ~30 wt% mass loss between the raw clay and activated product. Therefore, a 30 wt% mass loss was considered to account for free moisture, dehydration, dehydroxylation, and the presence of volatile matter including carbonates.

2.3.2.2. Thermal activation energy. The energy required for thermal

activation relates to drying, heating, and dehydroxylating clay particles, and is an important parameter influencing the environmental performance of thermally activated clays. The thermal activation energy demand at industrial scale is largely influenced by factors such as the technology used and its efficiency, and clay moisture and impurity contents. For the industrial scale data used, 95–98% of the energy consumed is sourced from fuels, with the remaining 2–5% supplied through steam and air.

Primary data were obtained for industrial production using rotary retrofitted, rotary double-body, and flash calciners. Literature data were obtained for conventional existing rotary (single-body) kilns. The compiled values from industry and literature are given in Fig. S3 of Supplementary Material S1 (Section S5). These include the energy required to dry, heat, and dehydroxylate the clay, and any losses. Fig. 2 shows the ranges of thermal activation energies for each technology. The average values were used in the LCA modelling.

2.3.2.3. Electrical energy consumption. Electricity is used in various stages of the thermal activation process, including pre-processing, activation, and post-processing. The total electricity consumed during rotary calcination is 20–25 kWh/t, and for flash calcination is ~35 kWh per tonne of activated clay. This discrepancy is due to the different processes involved (see Figs. S1 and S2, Supplementary Material S1), such as grinding required before activation in flash calcination and after activation in rotary kiln. The increased total electrical consumption for flash calcination is due to the requirement of lower sized input material (particle size) and additional processes based on the clay moisture content as explained in Supplementary Material S1(Section S3).

2.3.2.4. Input data and scenario analysis. The primary input data used for each technology considered here and for the default ‘calcined clay’ production in the ecoinvent database (which is based on unspecified technology and uses 100% pet coke) are listed in Table 2. The amount of clay input into the activation unit to produce 1.00 kg of activated clay is 1.45 kg. The corresponding amount of clay that needs to be extracted is 1.65 kg, considering 12% wastage during extraction, transportation, and pre-processing. Energy requirements for thermal activation range between 1.86 and 2.75 MJ per kg of activated clay (Fig. 2). Flash calcination has the lowest thermal activation energy and conventional existing (single-body) rotary kilns have the highest activation energy.

In the present study, scenario analysis was conducted to evaluate the impact of fuel type on the GWP of thermal activated clays. The energy sources used here are main fuels (coal, natural gas, and pet coke), alternative fuels such as wood pellets produced from saw dust, tyres,

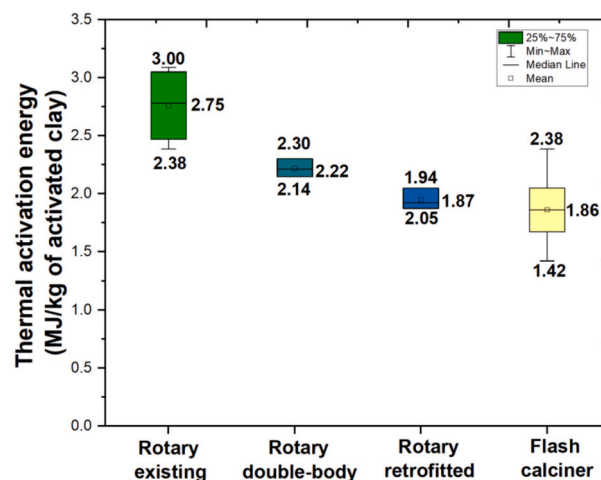


Fig. 2. Ranges of energy values for thermal activation of clays using different technologies.

Table 2
Primary input data used in the study to produce 1 kg of thermally activated clay.

Particulars (Input)	Rotary			Flash	Ecoinvent default
	Existing	Double body	Retrofitted		
Clay (kg)	1.45	1.45	1.45	1.45	1.3
Electricity consumed (kWh)	0.025	0.022	0.025	0.035	0.025
Thermal activation energy (MJ)	2.75	2.22	1.94	1.86	–
Fuel used (kg)					0.063
100% pet coke					

refuse-derived fuels (RDFs), and industrial wastes. Six scenarios were modelled considering the availability of fuels in the present and future, as listed below and in Table 3 (the percentages listed correspond to the amount of energy contributed by the fuel type to the total thermal activation energy requirement):

- 100% pet coke (also used in the ecoinvent dataset)
- 100% coal
- 100% natural gas
- 60% main fuels (25% pet coke, 25% coal, and 10% natural gas), and 40% alternative fuels (15% biomass, 10% RDFs, 5% tyres, and 10% other industrial wastes such as paints, used oils, solvents, plastics, carbon wastes, crap coke from coke filter in equal proportions); which is a typical fuel combination used in cement plants worldwide
- 10% pet coke and 90% alternative fuels (20% biomass, 20% RDFs, 5% tyres, and 45% other industrial wastes such as paints, used oils, solvents, plastics, carbon wastes, crap coke from coke filter in equal proportions)
- 100% alternative fuels (25% biomass, 25% RDFs, 5% tyres, and 45% other industrial wastes such as paints, used oils, solvents, plastics, carbon wastes, crap coke from coke filter in equal proportions)

We assumed that the type of fuel has no impact on the properties of thermally activated clay [30]. Processing required for waste derived alternative fuels such as biomass, tyres, and RDF was included using data from Georgiades et al. (2023) [3]. Other wastes like carbon black and paint sludge solvents were considered to not require processing to be utilised as fuel. The transportation distance for all alternative fuels was assumed to be 100 km from source to cement/activation plant. We considered biogenic and non-biogenic emissions from alternative fuels, which we assessed separately using GCCA emission factors [62]. The

Table 3
Fuel scenarios and the amounts of fuels used here to produce 1 kg of thermally activated clay.

Particulars (Input)	Rotary			Flash
	Existing	Double body	Retrofitted	
Fuel used* (kg)				
100% pet coke	0.085	0.068	0.059	0.057
100% coal	0.098	0.078	0.068	0.066
100% natural gas	0.057	0.046	0.040	0.039
60% main fuels and 40% alternative fuels	0.118	0.094	0.083	0.080
10% pet coke and 90% alternative fuels	0.147	0.118	0.103	0.100
100% alternative fuels	0.161	0.129	0.113	0.110

* Calculated based on the fuel calorific contents as per IPCC [63] and GCCA emission factors [62].

data and factors used in this study are provided in Supplementary Material S2.

The amount of fuel used based on the six scenarios ranges from 0.039 to 0.161 kg per kg of activated clay (Table 3). This variation depends on the thermal activation energy of the technology, fuel type and corresponding calorific content. Alternative fuels generally have lower calorific content (MJ/kg) than fossil fuels, therefore the amount required increases with higher substitutions rates. Fuels with higher calorific content and lower emissions by mass or energy content can reduce GWP by lowering the direct emissions during thermal activation.

3. Results and discussion

3.1. Effect of technology and fuel type

The GWP of the thermally activated clay assessed in this study varies from 0.186 to 0.360 kg CO₂-eq. per kg (Fig. 3). The majority of the GWP (60–75%) associated with activated clay produced in all the technologies considered here is from burning fuel for energy (direct emissions), which is associated with the type of fuel and technology adopted. Generally, fuel extraction contributes 8–10% of the GWP, while transportation of clay and fuels contribute 2–3%, and electricity use, and its production contributes 3–5%. Direct CO₂ emissions from decomposition of carbonates (typically calcite, < 5 wt% of clay) during calcination corresponds to 5–7% of the GWP. Carbonate decomposition emissions are not considered in the ecoinvent dataset ('CC' in Fig. 3). Impacts other than GWP are reported in Supplementary Material S1 (Section 6 and 7).

Of the four technologies modelled in this study, with the use of similar types of fuel (for example, pet coke), the results are a range of values from 0.259 to 0.360 kg CO₂-eq. per kg of thermally activated clay produced using a flash calciner (0.259 kg CO₂-eq. per kg) has lower GWP than that produced in conventional existing rotary kilns (0.360 kg CO₂-eq. per kg), and similar to that produced in rotary double-body (0.272 kg CO₂-eq. per kg) and retrofitted kilns (0.263 kg CO₂-eq. per kg). Therefore, changing the technology from existing conventional rotary to flash, rotary retrofitted, or rotary double-body can decrease the GWP by 24–28% (both biogenic and non-biogenic) when using a constant fuel (Fig. 3).

We calculate the GWP associated with production of 1 kg of thermally activated clay to be 0.186–0.259 kg CO₂-eq., 0.190–0.293 kg CO₂-eq., 0.210–0.293 kg CO₂-eq., and 0.250–0.360 kg CO₂-eq. for the flash, rotary retrofitted, rotary double-body, and conventional existing rotary systems, respectively. These values are consistent with GWP values reported by Miller et al. (2018) [64] for thermal activation of clay in a conventional existing rotary kiln (0.175–0.370 kg CO₂-eq. per kg of thermally activated clay), and with direct emissions reported by Vizcaino-Andrez et al. (2015) [31] for thermal activation (industrial scale) using rotary kilns with crude oil, i.e. 0.240 kg CO₂-eq. per kg activated clay (wet process) and 0.190 kg CO₂-eq. per kg (dry process). Our GWP results are slightly higher than that reported by Pillai et al. (2019) [40] of 0.130 kg CO₂-eq. per kg activated clay because of differences in the type and efficiency of technology, and fuels (kg CO₂/MJ) considered. Our results are also consistent with the GWP of thermally activated clay in the ecoinvent database which has a value of 0.272 kg CO₂-eq. per kg and 3.18 MJ per kg of thermally activated clay ('CC' in Fig. 3).

The fuel mix used has a significant effect on the GWP scores. Changing the fuel type can decrease the GWP by up to 30% (both biogenic and non-biogenic) and 43% (only non-biogenic) for a given technology or thermal activation energy requirement (Fig. 4). Considering both biogenic and non-biogenic emissions, the highest GWP is obtained when pet coke is used as the energy source (0.260–0.360 kg CO₂-eq. per kg thermally activated clay), and the lowest GWP is obtained using natural gas (0.186–0.250 kg CO₂-eq. per kg thermally activated clay). This variability in impacts associated with thermally

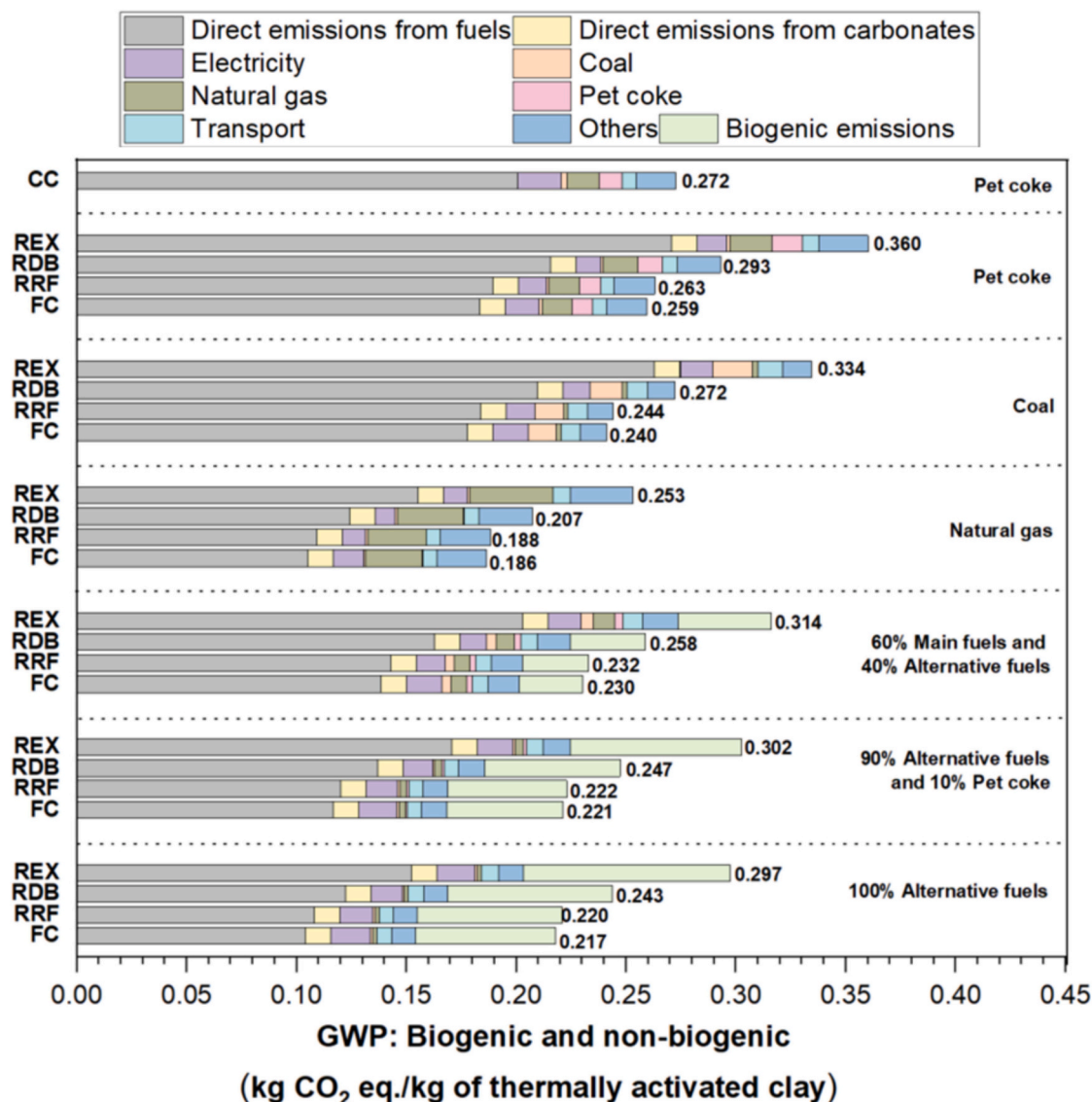


Fig. 3. GWP values for thermally activated clays produced using different technologies and fuels. The ecoinvent dataset shown here is 'Calcined clay production {RoW}' (Cutoff 3.91), which is for thermally activated clay production (referred as CC, calcined clay) using pet coke as fuel. REX: Rotary existing; RDB: Rotary double-body; RRF: Rotary retrofitted; FC: Flash calciner.

activated clay will have an influence on the corresponding cement produced.

Increasing alternative fuel use for thermal activation of clay increases biogenic CO₂-eq. emissions as biomass, RDFs, and tyres have modelled biogenic contents of 100%, 60% and 27%, respectively. The use of 100% alternative fuels does not lead to the lowest combined biogenic and non-biogenic GWP values; rather, it leads to intermediate GWP values between pet coke and natural gas (0.217–0.295 kg CO₂-eq. per kg activated clay). Utilising alternative fuels reduces both GWP and CED compared to pet coke since it avoids both direct emissions and fuel extraction. Processing of alternative fuels is only responsible for ~1% of the total emissions. The lowest non-biogenic GWP value (0.103 kg CO₂-eq.) is obtained for the 100% alternative fuels scenario in flash calcination. In general, the use of alternative fuels reduces all other impacts as shown in Table S6 of Supplementary Material S1 (Section S7).

3.2. Effect of carbonate content

Direct emissions from carbonate decomposition during thermal activation on average account for 0.010 and 0.102 kg CO₂ eq. per kg of

input clay with 0–5 wt% carbonates and > 5 wt% carbonates, respectively (Fig. 5). Direct emissions from thermal activation of clays with 5–50 wt% carbonates can contribute to as high as 52% of the total GWP for thermal clay activation (natural gas in flash calciner). Therefore, thermal activation of high carbonate containing clays should be avoided. For high carbonate containing clays, alternative activation technologies such as mechanochemical treatment could be considered since they can activate clays with high levels of calcite (up to 68%) without directly emitting CO₂ [16].

3.3. Comparison of thermally activated clays with other SCMs

We compare the GWP values of commonly used SCMs and thermally activated clay in Table 4. The GWP of thermally activated clays are greater than that of commonly used SCMs such as fly ash, GGBS, and fine limestone. This is due to the substantial energy required to thermally activate the clays. Freshly generated fly ash usually does not require activation; In contrast, if fly ash recovered from landfills require significant energy for drying (10–20% moisture content) and grinding, leading to a higher GWP. For GGBS, the cooled slag must be dried and

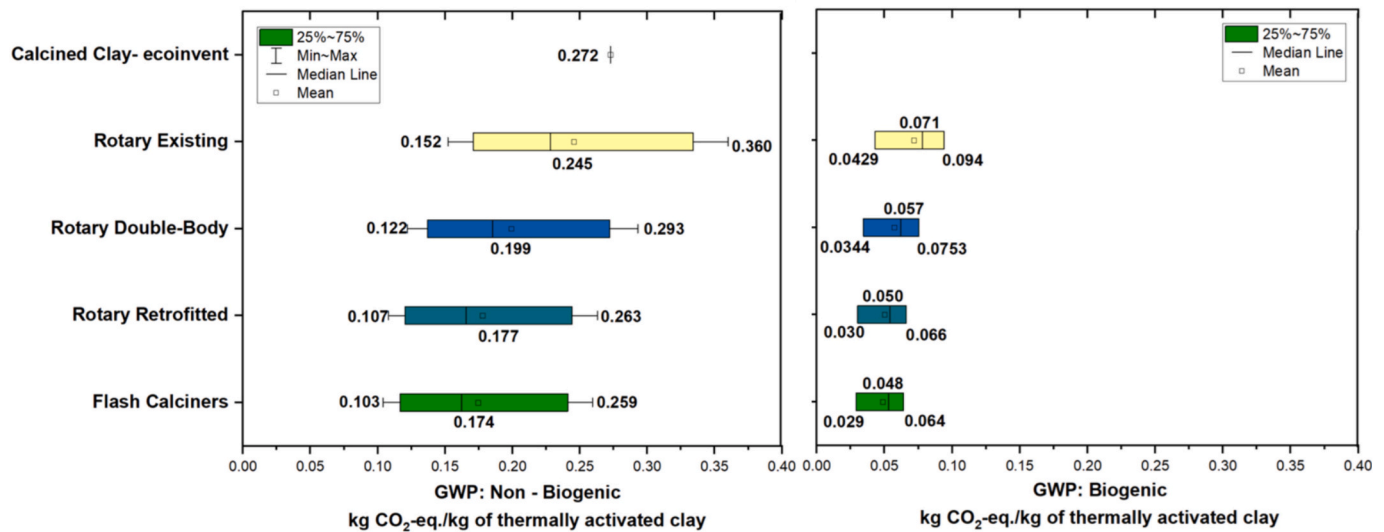


Fig. 4. Ranges of non-biogenic and biogenic GWP associated with thermally activated clays produced from different technologies and fuels.

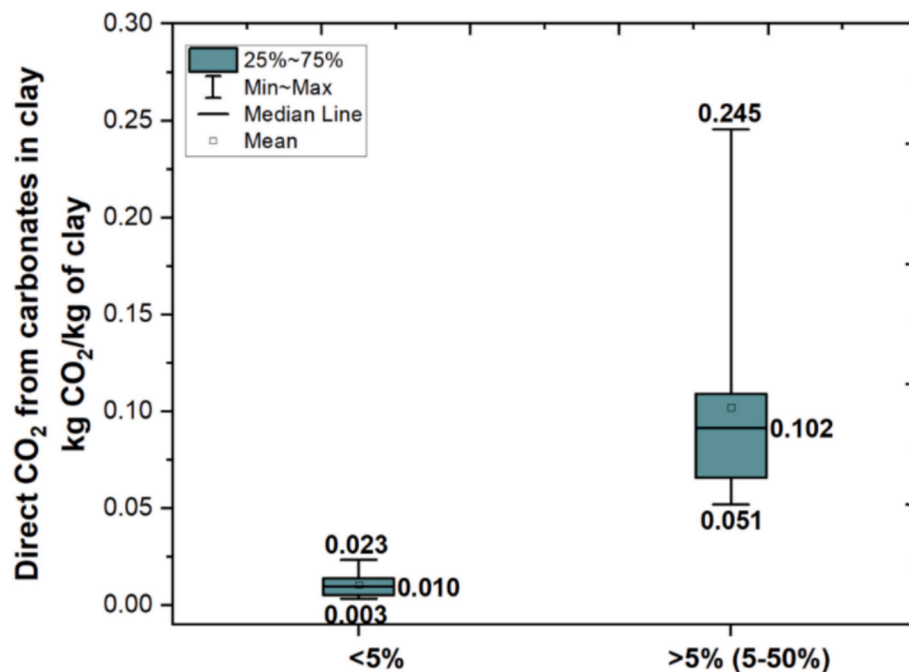


Fig. 5. Ranges of direct CO₂ emissions from the carbonates present in the 70 UK clay samples studied here (compositions from Tole et al., 2024 and 2025).

finely ground, but no activation is necessary, therefore the impacts are mainly due to electricity usage. Limestone, which is softer than GGBS, requires less electricity for grinding. Additionally, recycled concrete fines (RCFs) are reported to have negative carbon emissions based on carbonated end-to-life scenario.

3.4. Comparison of LC3 with other cements: GWP

Our results show that the GWP values for LC3-50 (50 wt% clinker, 30 wt% thermally activated clay, 15 wt% limestone, 5 wt% gypsum), LC3-35 (35 wt% clinker, 39 wt% thermally activated clay, 19 wt% limestone, 7 wt% gypsum) and LC3-25 (25 wt% clinker, 45 wt% thermally activated clay, 22.5 wt% limestone, 7.5 wt% gypsum) produced using thermally activated clays range from 0.520 to 0.580, 0.390–0.472 and 0.307–0.400 kg CO₂-eq. per kg cement (Fig. 6), respectively. The lower GWP values correspond to thermally activated clay produced

using flash calciner with 100% alternative fuels without considering biogenic emissions, while the higher GWP values correspond to thermally activated clay produced in a conventional existing rotary kiln using pet coke as fuel. If 100% natural gas is used to thermally activate the clay (case with lowest GWP, considering both biogenic and non-biogenic emissions), the lower band of the GWP score for LC3-50, LC3-35 and LC3-25 increases to 0.530, 0.405 and 0.322 kg CO₂-eq. per kg cement respectively. On average, thermally activated clay is responsible for ~10% (range: 6–14%), ~15% (range: 9–22%), and ~20% (range: 14–30%) of the GWP for LC3-50, LC3-35 and LC3-25, respectively. It should be noted that the range is dependent on the thermal activation technology and fuel used.

From Fig. 6, If we compare the GWP impacts of LC3-50, LC3-35 and LC3-25 with clinker, CEM-I and other blended PCs, without implying equivalent performance, to contextualise our results and the carbon footprint of LC3. The cement with lowest GWP is CEM-III/C, which

Table 4
Selected environmental impacts associated with different SCMs per kg.

SCM	GWP (kg CO ₂ eq.)	CED (MJ eq.)	Dataset/ reference
Thermally activated clays	total (0.103–0.360 non-biogenic, 0.029–0.094 biogenic)	2.7–4.7	Modelled in the present study
GGBS	0.098	1.9	ecoinvent - GGBS production - RoW
Recovered fly ash	0.22		Hafez et al., 2020 [65]
Fly ash	0.00877	0.833	Chen et al., 2020 [66]
Fine limestone	0.005	0.04	ecoinvent-Limestone for generic market of Supplementary Cementitious materials - RER
Recycled concrete fines (RCFs)	–0.065 to –0.12*		Driver et al., 2024 [67]

* The values are negative as they include CO₂ uptake during carbonation.

contains 88% GGBS, while the highest is CEM I, containing 90% clinker. The average GWP of LC3–50, LC3–35, and LC3–25 is lower by 32–40%, 45–54% and 53–64%, respectively compared to CEM–I. Since most impacts associated with cement production stem from clinker, reducing clinker content decreases the impacts of cement.

Cements are classified according to ‘strength class’ – a metric based on the compressive strength of standard mortars at different ages [50]. Therefore, LC3–50 can be classified as 42.5 N/R and 52.5 N/R depending on the type and reactivity of clay [68], the activated clay to limestone ratio [69], CEM I class used [70], sulfate adjustment [71], and grinding scenario [72,73]. Since LC3–25, LC3–35, and LC3–50 cements are still being gradually adopted, for comparison purposes in this study we considered the strength classes of LC3–25 and LC3–35 to be 32.5, and LC3–50 to be 42.5.

Strength classes of the other blended PCs included in the study

(Supplementary Materials S2, Table S3) were specified based on cements that are available in Europe [data provided in Supplementary Material S1] and are compared in Fig. 6. Our search for these cements focused on identifying at least one product in each cement type and strength class considered here. Within the 42.5 strength class, LC3–50 has lower GWP by 12–35% compared to CEM I, CEM IV/A, CEM II/B, CEM II/A; is similar to that of CEM III/A with 50% GGBS; and is 30% higher than CEM III/B with 73% GGBS. PCs with higher clinker replacement levels (>50%) such as CEM-IV/B, CEM V/B, CEM III/B, CEM III/C etc. are classified in the 32.5 strength class. Within this 32.5 strength class, LC3–35 and LC3–25 have ~30–50% lower GWP than CEM II/A, CEM II/B, CEM III/C and CEM IV/B, but not CEM III/C (with 88% GGBS), which has the lowest GWP (0.265 kg CO₂-eq./kg cement). This discussion should be interpreted noting the following limitation of strength-based comparisons derived from EN 197–1: This standard defines cement strength performance based on mortar testing at relatively high-water content, where workability constraints are low and not representative of practical concrete applications. In contrast, LC3-based concretes can have lower workability at equivalent water content compared to concretes made using CEM I–V cements [74]. Consequently, although two cements may fall within the same strength class, the resulting concrete may not exhibit equivalent performance without adjustments in mix design.

Concrete made with blended cements (such as CEM III/A, CEM III/B, CEM IV/A&B, CEM II/A–L, and CEM II/B) with at least 45 wt% CEM I, including LC3–50, has comparable compressive strength at 28 days [23,69,70,75]. Generally, CEM I can be replaced by LC3–50 to reduce the environmental impacts of concrete at similar performance [36,76]. Other blended PCs (including LC3–35 and LC3–25) could also be used by making corresponding changes to concrete mix design, such as the water-to-binder ratio, binder content, and aggregate ratio, adjusted to meet the desired strength performance [77]. In practical terms, maintaining both target strength and workability may require an increase in binder content in the absence of admixtures, whereas in industrial practice this is often mitigated using chemical admixtures rather than additional cement. This highlights that comparisons based solely on a

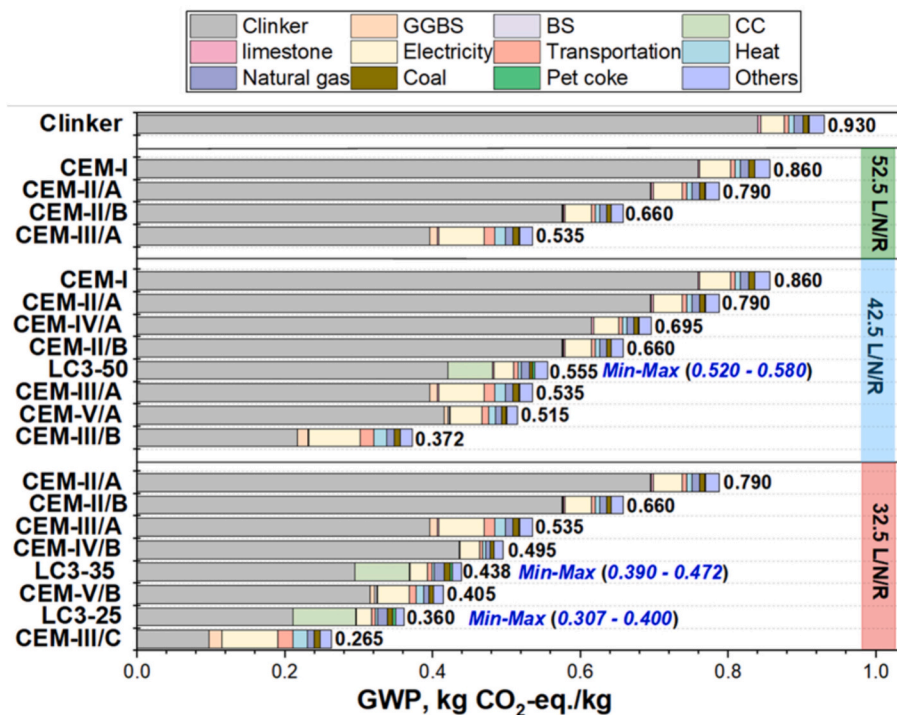


Fig. 6. Comparison of the GWP of LC3s and blended PCs standardised in EN 197–1:2011 [Table S3 and S2, Supplementary Material S1 - Section S4]. GGBS: Ground granulated blast furnace slag; BS: Burnt shale; CC: Calcined clay (thermally activated clay).

unit of cement mass and standardised strength class may not fully reflect field performance, particularly when workability requirements are considered. A more rigorous comparison would require defining functional equivalence at the concrete level (e.g., 28-day compressive strength, workability, and durability – all of which influenced by mix design approaches and locally-available materials), which may require different cement content (kg/m^3) and water demand. However, such a performance-based assessment is beyond the scope of the present study, which focuses on activated clay production and environmental impacts at this material level.

4. Conclusions

This work presents the first of its kind LCA study of activated clay production utilising primary data from industrial scale rotary kilns (existing single-body, retrofitted or double-body) and flash calciners with six fuel use scenarios. The environmental impacts of thermally activated clays mainly depend on the technology and fuel utilised. The 100-year global warming potential (GWP) associated with thermally activated clay is 186–259 $\text{kg CO}_2\text{-eq.}$, 190–293 $\text{kg CO}_2\text{-eq.}$, 210–293 $\text{kg CO}_2\text{-eq.}$, and 250–360 $\text{kg CO}_2\text{-eq.}$ per tonne of activated clay for the flash, rotary retrofitted single-body, rotary double-body, and conventional existing rotary single-body systems, respectively. The ranges of non-biogenic and biogenic GWP obtained from this study are 103–360 and 29–94 $\text{kg CO}_2\text{-eq.}$ per tonne of activated clay, respectively. Carbonates present in the clay increase direct CO_2 emissions due to decomposition during thermal activation. Clays with high ($> 5 \text{ wt\%}$) carbonate contents can have up to 52% higher GWP and should be activated using alternative methods such as mechanochemical activation. Regardless of the type of fuel used, thermally activated clay produced using a flash, rotary retrofitted, and rotary double-body kilns had lower GWP and CED values than that for conventional existing single-body kilns. GWP values differ by 60–100 $\text{kg CO}_2\text{-eq.}$ per tonne at constant fuel type and with variable activation technology, and by 40–70 or 100–200 (only non-biogenic) $\text{kg CO}_2\text{-eq.}$ per tonne at variable fuel type and constant activation technology. Changing the thermal activation technology can decrease GWP by 24–28% (both biogenic and non-biogenic) at constant fuel type. Changing the fuel type can decrease GWP by up to 30% (both biogenic and non-biogenic) and 43% (only non-biogenic) at constant technology. Thus, the results confirm the significance of technology and fuel types in the environmental performance of thermally activated clay. The production of activated clays contributes significantly to the values and uncertainties of environmental impacts of LC3. The GWP of LC3–50, LC3–35, and LC3–25 can vary up to 14%, 22% and 30%, respectively, depending on type of technology and fuels used to produce the activated clay. Although thermally activated clays have higher GWP than other commonly used SCMs, LC3 can achieve lower GWP than other blended PCs in the same cement strength class. The use of activated clay can significantly reduce the environmental impacts associated with cement and concrete due to the much higher environmental footprint of clinker production.

CRediT authorship contribution statement

Anusha S. Basavaraj: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Investigation, Formal analysis, Data curation, Conceptualization. **Maria Georgiades:** Writing – review & editing, Software. **Sofía Sánchez Berriel:** Writing – review & editing, Data curation. **Isabel Pol Segura:** Writing – review & editing, Data curation. **Fernando Martirena:** Writing – review & editing. **Wilson R. Leal da Silva:** Writing – review & editing. **Hong Wong:** Writing – review & editing, Resources, Project administration, Funding acquisition. **Rupert J. Myers:** Writing – review & editing, Visualization, Supervision, Resources, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cemconres.2026.108267>.

Data availability

All data used in this article is available in the Supporting Information files

References

- [1] K.L. Scrivener, Options for the future of cement, *Indian Concrete Journal* 88 (7) (2014) 11–21.
- [2] G. Habert, S.A. Miller, V.M. John, J.L. Provis, A. Favier, A. Horvath, K.L. Scrivener, Environmental impacts and decarbonization strategies in the cement and concrete industries, *Nat. Rev. Earth Environ.* 1 (11) (2020) 559–573.
- [3] M. Georgiades, I.H. Shah, B. Steubing, C. Cheeseman, R.J. Myers, Prospective life cycle assessment of European cement production, *Resour. Conserv. Recycl.* 194 (2023) 106998.
- [4] I.H. Shah, S.A. Miller, D. Jiang, R.J. Myers, Cement substitution with secondary materials can reduce annual global CO_2 emissions by up to 1.3 gigatons, *Nat. Commun.* 13 (1) (2022) 5758.
- [5] S. Alberici, J. De Beer, I. Van Der Hoorn, M. Staats, Fly Ash and Blast Furnace Slag for Cement Manufacturing, 2017.
- [6] E. Gartner, Industrially interesting approaches to “low- CO_2 ” cements, *Cem. Concr. Res.* 34 (9) (2004) 1489–1498.
- [7] K. Scrivener, F. Martirena, S. Bishnoi, S. Maity, Calcined clay limestone cements (LC3), *Cem. Concr. Res.* 114 (2018) 49–56.
- [8] J. Sun, F. Zunino, K. Scrivener, Hydration and phase assemblage of limestone calcined clay cements (LC3) with clinker content below 50%, *Cem. Concr. Res.* 177 (2024) 107417.
- [9] D. Zhou, R. Wang, M. Tyrer, H. Wong, C. Cheeseman, Sustainable infrastructure development through use of calcined excavated waste clay as a supplementary cementitious material, *J. Clean. Prod.* 168 (2017) 1180–1192.
- [10] K.D. Musbau, J.T. Kolawole, A.J. Babafemi, O.B. Olalusi, Comparative performance of limestone calcined clay and limestone calcined laterite blended cement concrete, *Cleaner Eng. Technol.* 4 (2021) 100264.
- [11] B. Ayati, D. Newport, H. Wong, C. Cheeseman, Low-carbon cements: potential for low-grade calcined clays to form supplementary cementitious materials, *Cleaner Mater.* 5 (2022) 100099.
- [12] Y. Dhandapani, A.T. Marsh, S. Rahmon, F. Kanavaris, A. Papakosta, S.A. Bernal, Suitability of excavated London clay as a supplementary cementitious material: mineralogy and reactivity, *Mater. Struct.* 56 (10) (2023) 174.
- [13] T. Hanein, K.C. Thienel, F. Zunino, A.T. Marsh, M. Maier, B. Wang, M. Canut, M.C. G. Juenger, F. Avet, A. Prashar, L.A. Al-Jaberi, Almenares – Reyes, R. S., Alujas-Diaz, A., Scrivner, K.L., Bernal, S., Provis, J.L., Sui, T., Bishnoi, S. & Martirena-Hernandez, F., Clay calcination technology: state-of-the-art review by the RILEM TC 282-CCL, *Mater. Struct.* 55 (1) (2022) 3.
- [14] R. Snellings, R. Almenares Reyes, T. Hanein, E.F. Irassar, F. Kanavaris, M. Maier, A. Alujas Diaz, Paper of RILEM TC 282-CCL: mineralogical characterization methods for clay resources intended for use as supplementary cementitious material, *Mater. Struct.* 55 (5) (2022) 149.
- [15] I. Tole, F. Delogu, E. Qoku, K. Habermehl-Cwirzen, A. Cwirzen, Enhancement of the pozzolanic activity of natural clays by mechanochemical activation, *Constr. Build. Mater.* 352 (2022) 128739.
- [16] V.A. Baki, X. Ke, A. Heath, J. Calabria-Holley, C. Terzi, Improving the pozzolanic reactivity of clay, marl and obsidian through mechanochemical or thermal activation, *Mater. Struct.* 57 (1) (2024) 9.
- [17] J.F.M. Hernández, R. Almenares-Reyes, F. Zunino, A. Alujas-Diaz, K.L. Scrivener, Color control in industrial clay calcination, *RILEM Technical Letters* 5 (2020) 1–7.

- [18] M. Canut, S. Miller, M. Joln s, Calcined clay: Process impact on the reactivity and color, in: *Calcined Clays for Sustainable Concrete*, Springer, Singapore, 2020, pp. 163–167.
- [19] R. Fernandez, F. Martirena, K.L. Scrivener, The origin of the pozzolanic activity of calcined clay minerals: A comparison between kaolinite, illite and montmorillonite, *Cem. Concr. Res.* 41 (1) (2011) 113–122.
- [20] R. Snellings, Y. Almenares Reyes, T. Hanein, E.F. Irassar, F. Kanavaris, M. Maier, A. T. Marsh, L. Valentini, F. Zunino, A. Aluj s Diaz, Paper of RILEM TC 282-CCL: mineralogical characterization methods for clay resources intended for use as supplementary cementitious material, *Mater. Struct.* 55 (5) (2022) 149.
- [21] B. Lothenbach, G. Le Saout, E. Gallucci, K. Scrivener, Influence of limestone on the hydration of Portland cements, *Cem. Concr. Res.* 38 (6) (2008) 848–860.
- [22] Y. Dhandapani, M. Santhanam, R. Gettu, R.G. Pillai, Perspectives on blended cementitious systems with calcined clay-limestone combination for sustainable low carbon cement transition, *Indian Concrete Journal* 94 (2) (2020) 31–45.
- [23] F. Zunino, Y. Dhandapani, M. Ben Haha, J. Skibsted, S. Joseph, S. Krishnan, F. Avet, Hydration and mixture design of calcined clay blended cements: review by the RILEM TC 282-CCL, *Mater. Struct.* 55 (9) (2022) 234.
- [24] C. He, B. Osbaeck, E. Makovicky, Pozzolanic reactions of six principal clay minerals: activation, reactivity assessments and technological effects, *Cem. Concr. Res.* 25 (8) (1995) 1691–1702.
- [25] A. Aluj s, R. Fern ndez, R. Quintana, K.L. Scrivener, F. Martirena, Pozzolanic reactivity of low grade kaolinitic clays: influence of calcination temperature and impact of calcination products on OPC hydration, *Appl. Clay Sci.* 108 (2015) 94–101.
- [26] S. Krishnan, A.C. Emmanuel, V. Shah, A. Parashar, G. Mishra, S. Maity, S. Bishnoi, Industrial production of limestone calcined clay cement: experience and insights, *Green Materials* 7 (1) (2018) 15–27.
- [27] J. Maia, P. Ladeira, A Focus on Flash Calcining, Tradership Publications Ltd, International Cement Review, 2021.
- [28] J. Maia, P. Ladeira, Clay Calcining Technologies: The Rotary Kiln Approach, Tradership Publications Ltd, International Cement Review, 2020.
- [29] J.F.M. Hern ndez, M. Antoni, Y. Oquendo-Machado, R. Borrajo-Perez, A. Aluj s-Diaz, R. Almenares-Reyes, Impact of calcination technology on properties of calcined clays, *RILEM Technical Letters* 8 (2023) 190–197.
- [30] A. Koutsouradi, T.R. Muzenda, P.A. Jensen, W.R.L. da Silva, A.J. Dam , F. Georget, T. Matschei, Impact of clay calcination method on the physicochemical properties of limestone calcined-clay cement, *Constr. Build. Mater.* 473 (2025) 140939.
- [31] L.M. Vizcaino Andres, M.G. Antoni, A. Aluj s Diaz, J.F. Martirena Hernandez, K. L. Scrivener, Effect of fineness in clinker-calcined clays-limestone cements, *Adv. Cem. Res.* 27 (9) (2015) 546–556.
- [32] W. Wulandari, A.T. Mursito, F.J. Juanjaya, M.F. Alwi, Performance of dolomite calcination in a bench-scale rotary kiln, in: *MATEC Web of Conferences* vol. 156, EDP Sciences, 2018, p. 06008.
- [33] S. Bishnoi, S. Maity, A. Mallik, S. Joseph, S. Krishnan, Pilot scale manufacture of limestone calcined clay cement: the Indian experience, *Indian Concr. J* 88 (6) (2014) 22–28.
- [34] R.S. Almenares, L.M. Vizc  no, S. Damas, A. Mathieu, A. Aluj s, F. Martirena, Industrial calcination of kaolinitic clays to make reactive pozzolans, *Case Stud. Constr. Mater.* 6 (2017) 225–232.
- [35] S.S. Berriel, A. Favier, E.R. Dom nguez, I.S. Machado, U. Heierli, K. Scrivener, G. Habert, Assessing the environmental and economic potential of limestone calcined clay cement in Cuba, *J. Clean. Prod.* 124 (2016) 361–369.
- [36] R. Gettu, A. Patel, V. Rath, S. Prakashan, A.S. Basavaraj, S. Palaniappan, S. Maity, Influence of supplementary cementitious materials on the sustainability parameters of cements and concretes in the Indian context, *Mater. Struct.* 52 (1) (2019) 10.
- [37] Y.C. D  az, S.S. Berriel, U. Heierli, A.R. Favier, I.R.S. Machado, K.L. Scrivener, G. Habert, Limestone calcined clay cement as a low-carbon solution to meet expanding cement demand in emerging economies, *Development Engineering* 2 (2017) 82–91.
- [38] K.L. Scrivener, V.M. John, E.M. Gartner, Eco-efficient cements: potential economically viable solutions for a low-CO₂ cement-based materials industry, *Cem. Concr. Res.* 114 (2018) 2–26.
- [39] S.A. Miller, R.J. Myers, Environmental impacts of alternative cement binders, *Environ. Sci. Technol.* 54 (2) (2019) 677–686.
- [40] R.G. Pillai, R. Gettu, M. Santhanam, S. Rengaraju, Y. Dhandapani, S. Rathnarajan, A.S. Basavaraj, Service life and life cycle assessment of reinforced concrete systems with limestone calcined clay cement (LC3), *Cem. Concr. Res.* 118 (2019) 111–119.
- [41] C.S. Malacarne, M.R.C. da Silva, S. Danieli, V.G. Maciel, A.P. Kirchheim, Environmental and technical assessment to support sustainable strategies for limestone calcined clay cement production in Brazil, *Constr. Build. Mater.* 310 (2021) 125261.
- [42] W.J. Long, C. Lin, J.L. Tao, T.H. Ye, Y. Fang, Printability and particle packing of 3D-printable limestone calcined clay cement composites, *Constr. Build. Mater.* 282 (2021) 122647.
- [43] E.S.A. Junior, N.T. de Sales Braga, M.S. Barata, Life cycle assessment to produce LC₃ cements with kaolinitic waste from the Amazon region, Brazil. *Case Studies in Construction Materials* 18 (2023) e01729.
- [44] A.S. Basavaraj, H. Muni, Y. Dhandapani, R. Gettu, M. Santhanam, Limestone-calcined clay (LC2) as a supplementary cementitious material for concrete, *RILEM Technical Letters* 8 (2023) 12–22.
- [45] D.M. Mart  nez, A. Horv  th, P.J. Monteiro, Comparative environmental assessment of limestone calcined clay cements and typical blended cements, *Environmental Research Communications* 5 (5) (2023) 055002.
- [46] W. Jin, C. Roux, C. Ouellet-Plamondon, J.F. Caron, Life cycle assessment of limestone calcined clay concrete: potential for low-carbon 3D printing, *Sustain. Mater. Technol.* 41 (2024) e01119.
- [47] I. Tole, Y. Dhandapani, J.S. Kemp, T.M.M. Marsh, C. Mitchell, Unlocking the potential of the UK clays for the production of low-carbon cements, in: *2nd International conference on innovation in low-carbon cement and concrete technology*, London, 2024. July 2024, <https://eprints.whiterose.ac.uk/id/eprint/214896/>.
- [48] I. Tole, Y. Dhandapani, S.J. Kemp, A.T. Marsh, C. Mitchell, L. Black, H. Wong, S. A. Bernal, Impact of the mineralogy of low-purity clays on their suitability as supplementary cementitious materials, *Cem. Concr. Res.* 204 (2026) 108211.
- [49] BS 8615-1, Specification for Pozzolanic Materials for Use with Portland Cement, Natural Pozzolana and Natural Calcined Pozzolana, 2019.
- [50] BS EN 197-1:2011, Cement - Composition, specifications and conformity criteria for common cements, 2019.
- [51] N.A. Madlool, Assessment of waste preheater gas and dust bypass systems: Al-Muthanna cement plant case study, *Case Stud. Therm. Eng.* 8 (2016) 330–336.
- [52] I.P. Segura, N. Ranjbar, A.J. Dam , L.S. Jensen, M. Canut, P.A. Jensen, A review: alkali-activated cement and concrete production technologies available in the industry, *Heliyon* 9 (5) (2023).
- [53] A. Putin, “IPIAC’s Technology”. Pdf presented in LC3 Day in Costa Rica March, 26–29th 2023, 2023.
- [54] A. Teklay, C. Yin, L. Rosendahl, L.L. K  hler, Experimental and modeling study of flash calcination of kaolinite rich clay particles in a gas suspension calciner, *Appl. Clay Sci.* 103 (2015) 10–19.
- [55] A. Teklay, C. Yin, L. Rosendahl, Flash calcination of kaolinite rich clay and impact of process conditions on the quality of the calcines: A way to reduce CO₂ footprint from cement industry, *Appl. Energy* 162 (2016) 1218–1224.
- [56] J. Lemke, C. Berger, Thermal Processing of Calcined Clay, in: In: Martirena, F., Favier, A., Scrivener, K. (Eds) *Calcined Clays for Sustainable Concrete*. RILEM Bookseries, Vol 16, Springer, Dordrecht, 2018, https://doi.org/10.1007/978-94-024-1207-9_42.
- [57] G.G.O. Rodrigues, A.B. Rohden, V.R. Wiggers, M.R. Garcez, Reactivity of flash-calcined illitic clays, *Constr. Build. Mater.* 411 (2024) 134578.
- [58] S. Hollanders, Mineralogical Study of the Pozzolanic Properties of Calcined Clays, Arenberg Doctoral School, KU Leuven, 2017.
- [59] R. San Nicolas, M. Cyr, G. Escadell  s, Characteristics and applications of flash metakaolins, *Appl. Clay Sci.* 83 (2013) 253–262.
- [60] A. Tironi, F. Cravero, A.N. Scian, E.F. Irassar, Pozzolanic activity of calcined halloysite-rich kaolinitic clays, *Appl. Clay Sci.* 147 (2017) 11–18.
- [61] P. Pasabeyoglu, G. Moumin, L. De Oliveira, M. Roeb, B. Akata, Solarization of the zeolite production: calcination of kaolin as proof-of-concept, *J. Clean. Prod.* 414 (2023) 137611.
- [62] Global Cement and Concrete Association (GCCA), The cement CO₂ and Energy Protocol- Version 3, CO₂ and Energy accounting and reporting standard for the cement industry. https://www.cement-co2-protocol.org/en/Content/Resoures/Downloads/GCCA_Internet_Manual.pdf, 2008.
- [63] A. Garg, K. Kazunari, Pulles T (2007) 2006. IPCC Guidelines for National Greenhouse Gas Inventories IPCC <https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html>.
- [64] S.A. Miller, V.M. John, S.A. Pacca, A. Horv  th, Carbon dioxide reduction potential in the global cement industry by 2050, *Cem. Concr. Res.* 114 (2018) 115–124.
- [65] H. Hafez, R. Kurda, W.M. Cheung, B. Nagaratnam, Comparative life cycle assessment between imported and recovered fly ash for blended cement concrete in the UK, *J. Clean. Prod.* 244 (2020) 118722.
- [66] C. Chen, G. Habert, Y. Bouzidi, A. Jullien, A. Ventura, LCA allocation procedure used as an incitative method for waste recycling: an application to mineral additions in concrete, *Resour. Conserv. Recycl.* 54 (12) (2010) 1231–1240.
- [67] J.G. Driver, E. Bernard, P. Patrizio, P.S. Fennell, K. Scrivener, R.J. Myers, Global decarbonization potential of CO₂ mineralization in concrete materials, *Proc. Natl. Acad. Sci.* 121 (29) (2024) e2313475121.
- [68] F. Avet, K. Scrivener, Investigation of the calcined kaolinite content on the hydration of limestone calcined clay cement (LC3), *Cem. Concr. Res.* 107 (2018) 124–135.
- [69] Y. Dhandapani, M. Santhanam, Influence of calcined clay-limestone ratio on properties of concrete with limestone calcined clay cement (LC3), in: *Calcined Clays for Sustainable Concrete: Proceedings of the 3rd International Conference on Calcined Clays for Sustainable Concrete*, Springer Singapore, 2020, pp. 731–738.
- [70] F. Zunino, X. Li, J. Dengler, Technological approaches to improve early-age strength of limestone calcined clay cements, *Engineering* (2025), <https://doi.org/10.1016/j.eng.2025.03.029>.
- [71] H. Huang, X. Li, F. Avet, W. Hanpongpan, K. Scrivener, Strength-promoting mechanism of alkanolamines on limestone-calcined clay cement and the role of sulfate, *Cem. Concr. Res.* 147 (2021) 106527.
- [72] S. Krishnan, S. Bishnoi, Understanding the hydration of dolomite in cementitious systems with reactive aluminosilicates such as calcined clay, *Cem. Concr. Res.* 108 (2018) 116–128.
- [73] V. Shah, A. Parashar, G. Mishra, S. Medepalli, S. Krishnan, S. Bishnoi, Influence of cement replacement by limestone calcined clay pozzolan on the engineering properties of mortar and concrete, *Adv. Cem. Res.* 32 (3) (2020) 101–111.
- [74] N. Nair, K.M. Haneefa, M. Santhanam, R. Gettu, A study on fresh properties of limestone calcined clay blended cementitious systems, *Constr. Build. Mater.* 254 (2020) 119326.

- [75] A.C. Clear, Cement Type/Early Age Properties, 2012 (Sustainability -technical future).
- [76] Y. Dhandapani, K.K. Subramanian, F. Kanavaris, L. Black, S.A. Bernal, The meta-kaolinite content of the calcined clay source impacts the mechanical and durability performance of blended Portland concrete, *Cem. Concr. Res.* 196 (2025) 107922.
- [77] R. Gettu, R.G. Pillai, M. Santhanam, A.S. Basavaraj, S. Rathnarajan, B.S. Dhanya, Sustainability-based decision support framework for choosing concrete mixture proportions, *Mater. Struct.* 51 (2018) 1–16.