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Process-based life cycle assessment of waste clay for mineral carbonation and enhanced weathering: A case study for northeast England, UK

Mardin Abdalqadir [a], Sina Rezaei Gomari [a,*], David Hughes [a], Ahmed Sidiq [a], Feysal Shifa [b]

[a] Department of Engineering, School of Computing, Engineering and Digital Technologies, Teesside University, Middlesbrough, TS1 3BA, UK
[b] Scott Bros Limited, Scott Business Park, Haverton Hill Road, Stockton-On-Tees, Billingham, TS23 1PY, UK

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ABSTRACT

The potential of enhanced silicate rock weathering for long-term carbon dioxide sequestration is substantial, but it is dependent on the availability of suitable materials and proximity to appropriate field application locations. This paper evaluates the implementation of waste clay in the form of filter cake on agricultural land in northeast (NE) England for mineral carbonation (MC) and enhanced weathering (EW) over 26 years from 2024 to 2050. Process-based life cycle assessment (LCA) is used in this study to provide an effective evaluation of CO_2 emissions. Our results show that the potential levels of CO_2 sequestration of filter cake through MC and EW are 0.16t CO_{2eq}/t and 0.29t CO_{2eq}/t respectively. Considering the sequestration potential of 580,000 ha of agricultural land in the NE England, it is shown that the deployment of waste clay in the form of filter cake on that land could capture 0.77 to 1.62 Mt CO_{2eq} with an application rate of 11.2 t/ha for MC and EW respectively, while the corresponding CO_2 emissions throughout the application of the processes involved are calculated to be only 0.27 Mt CO_{2eq} over 26 years. This study demonstrates the importance of waste clay valorisation on agricultural soil in NE England in reducing CO_2 in the atmosphere and its role in the UK's 'Net Zero' ambition.

1. Introduction

Scientists have shown that, by 2100, the global temperature will increase by 2 °C if 3.3 Gt of CO_2 annually has not been removed directly from the atmosphere (Smith et al., 2016; Fawzy et al., 2020). To avoid this, it is not only necessary to limit the emission of greenhouse gases (GHG), but it is also important to reduce the amounts that already exist in the atmosphere (Minx et al., 2017; Nemet et al., 2018). Greenhouse gas removal (GHGR) technology has the potential and is expected to play an important role in reducing GHG (Minx et al., 2018; Jeswani et al., 2022). One GHGR technology is EW, involves the removal of CO_2 from the atmosphere by dissolving silicate minerals on the land surface (Renforth, 2012). EW has recently attracted significant interest due to its potential to reduce GHG in the atmosphere compared to other GHGR technologies (Beerling et al., 2020; Haque et al., 2021; Kantzas et al., 2022). Likewise, MC is a process that artificially promotes the formation of carbonate minerals in soils to create a permanent storage for atmospheric CO_2 (Washbourne et al., 2015; Kolosz et al., 2019; Jorat et al., 2020, 2022).

Over geological time, silicate rock weathering has been crucial in controlling the Earth's climate. However, natural rock weathering typically occurs at a slow rate (Lal, 2003), making its impact on human timescales insufficient to offset artificial changes to the composition of the atmosphere (Hartmann et al., 2009; Martin, 2017). To boost and accelerate the weathering process, MC and EW, which rely on mineral comminution, have been used to increase the reactive surface of rock, promote dissolution, and thus enhance the rate of CO_2 capture (Moosdorf et al., 2014; Haque et al., 2019a; Chai et al., 2021).

The overall carbon capture potential of EW strongly depends on the application area (Taylor et al., 2021), the type of materials used being rich in calcium and magnesium (Manning et al., 2013), grain size (Rinder and von Hagke, 2021), mineralogy (Lewis et al., 2021), climatic conditions (Andrews and Taylor, 2019), land cover (Vakilifard et al., 2021) and rate of application (Deng et al., 2023). Possible sources of calcium and magnesium to form paedogenic carbonates include silicate rocks rich in natural Ca^{+2} and Mg^{+2} such as olivine (Oelkers et al., 2018), basalt (Manning et al., 2013), dunite (Amann et al., 2020) and wollastonite (Haque et al., 2019b).

The potential of EW in removing atmospheric CO_2 has been estimated using various approaches. These include modelling studies (Taylor et al., 2016, 2017; Beerling et al., 2020; Bullock et al., 2021; Haque et al., 2023), and laboratory experiments led by Pogge von

* Corresponding author.
E-mail address: s.rezaei-gomari@tees.ac.uk (S. Rezaei Gomari).

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Strandmann et al. (2021) have also contributed to these estimations. Furthermore, data have also been employed from small-scale (Kelland et al., 2020), and large-scale investigations (Larkin et al., 2022; Guo et al., 2023; Knapp et al., 2023).

Basalt and dunite have generally been employed in various types of land cover, such as cropland, vegetated land, and forests. The CO_2 removal efficiency of basalt in varying land covers produced ranges between 1.8 and 44 Gt CO_{2eq}/year (Hartmann and Kempe, 2008; de Oliveira Garcia et al., 2020). Meanwhile, dunite has a significantly higher CO_2 removal efficiency of about 95 Gt CO_{2eq}/year compared to basalt's highest CO_2 removal efficiency of 44 Gt CO_{2eq}/year (Strefler et al., 2018).

Moreover, silicates rich in Ca^{+2} and Mg^{+2} can be found in waste streams such as demolition waste and basic steel slags (Renforth, 2019; Jia et al., 2022). More than one billion tonnes of such waste are available globally, with a carbon sequestration potential of 100 million tonnes per annum (Renforth et al., 2011).

Jia et al. (2022) and Zhang et al. (2023) conducted field studies in the province of Shandong in China using non-hazardous industrial wastes such as steel slag, mine tailings, coal fly ash, and desulphurisation gypsum in order to sequester CO_2. According to their findings, it is projected that non-hazardous industrial waste could contribute to the fixation of approximately 306 Mt CO_{2eq} from 2020 to 2030 (equivalent to approximately 12.73 Mt to 13.77 Mt CO_{2eq} per year). Furthermore, Renforth (2019) observed that silicate minerals obtained from waste materials exhibit a carbonation efficiency that is 10%–60% higher than that of natural silicate resources that have not undergone any processing. However, that study did not take into account the effect of specific application fields and climate conditions on EW.

Life cycle assessment (LCA) has been used as an efficient technique in estimating the environmental footprint of MC (Khoo et al., 2011, 2021; Nduagu et al., 2012; Thonemann et al., 2022) and EW (Tan and Aviso, 2021).

To date, only a few research papers have been published regarding the LCA analysis of EW, which includes the assessment of its environmental and human health impact. Lefebvre et al. (2019) and Eufrasio et al. (2022) considered pulverised basalt rock as a raw material in their studies, while Koornneed and Nieuwlaar (2009) and Cooper et al. (2022) explored olivine as a potential raw material. According to the research findings, transportation and comminution processes were identified as two primary factors that have an impact on both the environment and human health. Furthermore, Lefebvre et al. (2019) proposed a carbon dioxide removal (CDR) potential ranging from 1.3 to 2.4 Mt/y by applying three different rates (5, 20, 50 ton/ha) of pulverised basalt on agricultural land in Sao Paolo State, Brazil. However, no previous studies have been conducted of LCA for MC and EW under ambient earth conditions using waste materials such as demolition waste.

Therefore, the purpose of this research is to determine the environmental impact of the use of fine waste clay in the form of filter cake on agricultural soil in NE England, United Kingdom, for MC and EW. The environmental impact is quantified in terms of relative CO_2 emissions over 26 years from 2024 to 2050, including the emissions released from the collection of demolition waste and spreading it on agricultural land. The Scott Bros Ltd company produces around 250,000 tonnes of fine waste clay in the form of filter cake per year. Their product has been chosen for this study as it has a suitable mineral composition for the carbonation process, including magnesium and calcium ions, as well as a particle size below 1.5 mm which enhances its sequestration potential. This paper also demonstrates how the EW process can play a major role in valorising waste materials for the capture of CO_2 from the atmosphere and its permanently storage in soil in the form of calcium carbonate.

2. Methodology

2.1. Waste clay production

According to research conducted by the Department for Environment, Food and Rural Affairs. (2020), a total of 54 million tonnes of non-hazardous construction and demolition waste was produced in the UK in 2020 alone. Almost 50 million tonnes of this was recycled, and 4 million tonnes remained as waste.

Scott Bros Ltd (Teesside, UK) provided the waste clay filter cake used in the present study. This company collects and processes combined soil waste from the construction industry throughout NE England (UK), including County Durham, North Yorkshire and Teesside. Following initial categorisation, the mixed soil waste is then processed at a soil wash plant on Teesside. This process entails the cleaning of any polluted bulk soils as well as separating it according to individual particle size ranges such as fine, sand, gravel and cobbles. The coarser-grained particle fractions of washed soil debris can be reused as aggregates in a variety of construction products such as pavements and concretes. The fine-grained waste left on the belt press within the wash plant is collected to produce 'filter cake'. This includes extremely saturated silt and clay fractions that do not yet have a direct reuse application. Based on the optimised operational frequency and capacity of the Scott Bros Ltd wash plant, approximately 250,000 tonnes of soil waste are processed per annum, which is about 6.25% of the total non-hazardous construction and demolition waste produced in England. This amount was used as the reference value in the LCA evaluation in this research.

2.2. Characterisation of waste clay

Major elemental analysis expressed in oxide form was carried out by X-ray fluorescence (XRF) analysis using a Philips PW1480 X-ray fluorescence spectrometer to determine the amounts of chemical elements present in the filter cake, especially of CaO and MgO. Glass disc used to measure the major elements, while pressed powder was used for analysing trace elements. As for quality control, the XRF machine was calibrated using various certified standards, including British Chemical Standards (BCS) such as BCS372/1 (hydrated cement), BCS376 (potassium feldspar), and BCS375 (sodium feldspar). The accuracy and precision achieved through this calibration process were 0.5–3% and less than 2%, respectively.

The XRF results indicate that the main constituents are silicon, aluminium, calcium, and iron, with smaller percentages of magnesium, potassium, titanium, and sodium, as shown in Table 1. Notably, there were low amounts of trace elements such as copper and Nickel, with copper being the most prominent one at 0.11% in the chemical composition of the filter cake.

The moisture content of the filter cake was 42.26%, determined using the method defined in BS 1377–2:2022, Part 11.3. The pH of the filter cake was measured using a pH meter (Fisher Scientific), revealing an alkaline pH value of 8.1. The particle size distribution analysis of the filter cake was conducted at Exploration & Testing Associates, UK. The results are presented in Table 1 and Fig. 1a, indicating that the majority of particles are silt, with particle sizes ranging between 0.063 and 0.002 mm. The mineralogical composition of the filter cake was analysed using a Siemens D500 powder diffractometer with Cu radiation, $\lambda = 0.154056$ nm at 40 kV and 20 mA. Data were obtained in a radiation scope of 10°–70° (2θ) with a step time of 0.2 s and 0.01° phase scale and the data were evaluated by Profex software (version 5.2.1) using the Rietveld Refinement technique. The result of the XRD analysis of the filter cake is presented in Fig. 1b, showing that the main minerals in the filter cake are quartz (35.2%), anorthite (29.3%), chlorite (18.9%), albite (9.5%) and calcite (7.1%) as listed in Table 1.

Table 1
Chemical composition, moisture content, pH, particle size and mineralogical composition of filter cake.

		Trial 1 (wt)%	Trial 2 (wt)%	Trial 3 (wt)%	Average (wt)%	Standard deviation (σ)
Chemical composition	SiO_2	47.85	47.62	47.4	47.62	0.18
	$Al2O_3$	16.93	16.88	17.07	16.96	0.08
	Fe_2O_3	11.87	11.81	11.88	11.85	0.03
	CaO	15.34	15.19	15.24	15.26	0.06
	MgO	3.86	3.98	3.82	3.89	0.07
	K_2O	2.57	2.51	2.59	2.56	0.03
	TiO_2	1.05	1.04	1.09	1.06	0.02
	Na_2O	0.92	1.08	0.95	0.98	0.07
Moisture content		42.25	42.21	42.3	42.26	0.04
Particle size	Gravel (>2.0 mm)	0	1	2	1	0.82
	Sand (2.0–0.063 mm)	17	20	17	18	1.41
	Silt (0.063–0.002 mm)	64	61	58	61	2.45
	Clay (<0.002 mm)	19	18	23	20	2.16
Mineralogical composition	Anorthite	28.4	30.5	29.1	29.3	0.87
	Albite	9.8	9.2	9.5	9.5	0.24
	Calcite	7	6.9	7.4	7.1	0.22
	Chlorite	18.6	19.6	18.5	18.9	0.50
	Quartz	36.2	33.8	35.5	35.2	1.01
pH		8.18	8.05	8.07	8.1	0.06

* **Note**: number of trail (n) = 3.

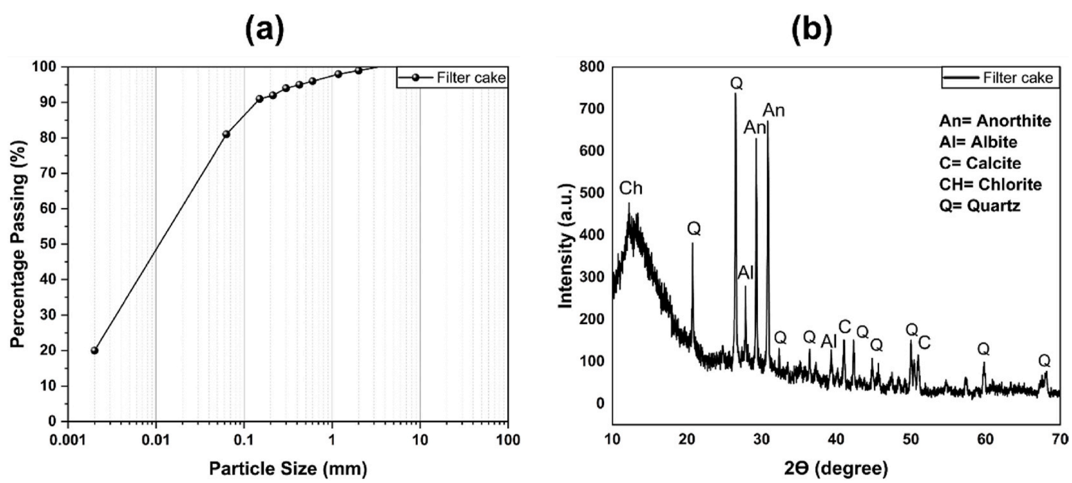

Fig. 1. Characterisation of filter cake: **(a)** particle size distribution; **(b)** XRD analysis.

2.3. EW and MC process

In terms of the chemical aspects involved, rock weathering undergoes a combination of chemical reactions. The first process is the hydration of CO_2, which reacts with water to create the weak acid H_2CO_3 as shown in **Eq. (1)** (Martin, 2017):

$$CO_2 + H_2O \rightarrow H_2CO_3 \quad (1)$$

When this weak acid reacts with silicate rock, it breaks it down and releases base cations such as Ca^{+2} and Mg^{+2} and carbonate and bicarbonate ions. **Eq. (2)** shows the weathering of wollastonite (Beerling, 2017):

$$CaSiO_3 + 2H_2CO_3 \rightarrow Ca^{+2} + 2HCO_3^- + SiO_2 + H_2O \quad (2)$$

Furthermore, the dissolved bicarbonate ions will be transferred to the ocean via the porous media of the ground or soil, and 2 mol of CO_2 will be captured per mole of calcium. The period starting from CO_2 hydration until the release of bicarbonates into the ocean and the capture CO_2 can be described as the process of enhanced weathering, as in **Eq. (3)** (Lefebvre et al., 2019):

$$CaSiO_3 + 2CO_2 + 2H_2O \rightarrow Ca^{+2} + 2HCO_3^- \text{(Ocean)} + SiO_2 + H_2O \quad (3)$$

MC can occur if the soil conditions are appropriate for the reaction to take place, where a minority of calcium and magnesium cations are precipitated to generate the carbonate minerals. Here, a half mole of CO_2 will be sequestrated. The process of MC is illustrated in **Eq. (4)** (Lefebvre et al., 2019):

$$CaSiO_3 + 2CO_2 + 2H_2O \rightarrow Ca^{+2} + 2HCO_3^- + SiO_2 + H_2O$$

$$Ca^{+2} + 2HCO_3^- \leftrightarrow CaCO_3 \text{ (in soil)} + CO_2 + H_2O \quad (4)$$

The sequestration potential of EW and MC strongly depends on the type of feedstock used, such as natural rock or waste materials, and its availability. Minerals in the form of ultrabasic rocks such as olivine and basalt undergo weathering relatively rapidly and appear to have higher potential for CO_2 sequestration (O'Connor et al., 2005). However, various studies suggest that the weathering of some ultrabasic rocks such as olivine and basalt may cause the release of nickel (Ni) and chromium (Cr) into the environment. If sufficient quantities are released, this may inhibit plant calcium uptake and could be toxic (Bryan and Ernst, 2008; ten Berge et al., 2012; Renforth et al., 2015; Kantola et al., 2017; Beerling et al., 2018; Strefler et al., 2018). Non-hazardous construction and demolition waste such as filter cake is available in large quantities across the world and has no or minimal concentrations of Cr and Ni metals.

2.4. CO_2 sequestration potential of waste clay

The sequestration potential of filter cake has been calculated using Eq. (5) (Renforth, 2012):

$$R_{CO2} = \frac{M_{CO2}}{100}\left(\frac{\%CaO}{M_{CaO}} + \frac{\%MgO}{M_{MgO}}\right) \times \omega \tag{5}$$

where RCO_2 is the sequestration potential in tonnes of CO_{2eq} per tonne of rock; MMgO, MCaO, and MCO_2 are the molecular masses of MgO, CaO and CO_2 respectively; %CaO and %MgO are the percentages in weight of CaO and MgO respectively in the rock; and ω is a factor that accounts for the additional sequestration that occurs when cations are transported to the ocean and remain dissolved and this factor can differ from one process to another. In carbonation, no cations reach the ocean, and so the value of ω is 1. On the other hand, EW involves the transportation of cations to the ocean followed by its storage in deep ocean layers. Here the value of ω is 1.79, which means 1.79 mol of CO_2 captured per mole of MgO or CaO. Moreover, the molecular masses of CO_2, CaO and MgO are constant at 44.01, 56.08 and 40.30 respectively. The potential of feedstocks to sequestrate CO_2 is highly dependent on the amounts of calcium and magnesium present in the minerals (Renforth, 2019). The elemental analysis using XRF in this study showed that the average CaO and MgO contents were 15.26 ± 0.06 and 3.89 ± 0.07% by weight respectively. This research considers the EW and MC pathways. Although MC will occur after the application of rock onto the land (Manning and Renforth, 2013), EW is anticipated to occur simultaneously and additional carbonation-produced calcite and magnesite dissolution could potentially take place (Landi et al., 2003). As a result, the actual sequestration value following the application of one tonne of filter cake to a field is likely to fall between the lower and upper bounds of the MC and EW sequestration potentials, which are presented here as lower and upper bounds respectively.

2.5. Life cycle analysis for waste clay application

2.5.1. Quantitative approach

LCA can be implemented using one of three fundamental methodologies: 1) input-output hybrid-based LCA; 2) process-based LCA; or 3) hybrid LCA (Buyle et al., 2013). Each method has disadvantages and advantages depending on the objective and scope of an LCA study. The process-based method enables good comparison options and is thus a more effective evaluation of the results of a case study (Pieragostini et al., 2012). In order to calculate the CO_2 emissions from spreading filter cake over agricultural land in NE England, the current study uses a process-based LCA methodology. Based on ISO 14044, key steps in the LCA methodology include goal and scope definition, inventory analysis, impact assessment, and interpretation (International Organization for Standardization, 2006).

2.5.2. Scope definition

This study offers a framework for the evaluation of CO_2 emissions and the recognition of significant sources of CO_2 emissions when applying filter cake for MC and EW on agricultural land in NE England. NE England was chosen as the target area of this study for the following appealing reasons: i) close proximity to the source of filter cake production, thus translating into savings in terms of CO_2 emissions; ii) favourable climate conditions for rapidly enhanced weathering; iii) limited capacity of filter cake to supply all agricultural land across the entire nation.

The total agricultural area of NE England is 580,000 ha (Department for Environment Food & Rural Affairs, 2023). Fig. 2 illustrates the agricultural land within NE England. The average distance from the source of filter cake production to the field application sites is assumed to be 65 km, based on three different locations at Middlesbrough (10 km), Newcastle (65 km), and Berwick upon Tweed (162 km). These locations represent close, moderate, and far transportation scenarios in NE agricultural land.

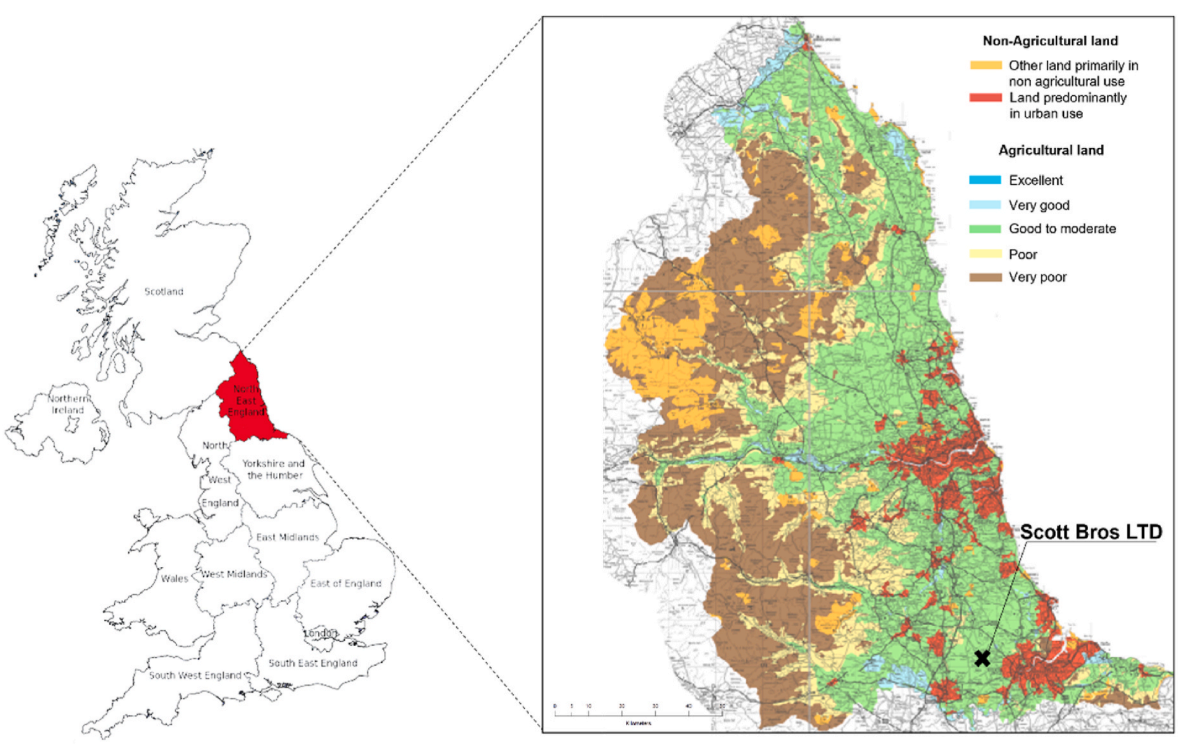

Fig. 2. Agricultural land in NE England, United Kingdom (modified from Natural England, 2011).

2.5.3. System boundaries

Scott Bros Ltd only uses diesel as an energy source in the process of filter cake production, and that is the only energy resource involved in all of the processes considered in this study. The following processes were taken into account in assessing the environmental effect in terms of CO_2 emissions of the application of filter cake: collection of waste materials from the construction site; transportation of waste materials from construction sites to Scott Bros Ltd; production of filter cake; its transport to each site; and its spreading on site (Fig. 3). However, crushing was not considered in this study because the filter cake consists of fine particles. This LCA does not account for any soil response or crop production after the field application. The functional units (FUs) in this LCA are: i) per tonne of $CO2_{eq}$ removed per year; ii) per tonne of CO_{2eq} produced per year; and iii) per hectare of NE England agricultural land. According to previous research (Ramezanian et al., 2013; Beerling et al., 2018; Lefebvre et al., 2019), the minimum and maximum application rates of silicate rock are 5 and 50 t/ha respectively. Since there is no previous research on the use of waste materials for enhanced weathering, we assumed that the filter cake could act as a suitable substitute for rock dust due to its mineralogical composition and fine particle size. Considering the availability of filter cake, with Scott Bros producing 250,000 tons of it, we selected an application rate of 11.2 t/ha. This rate also serves as the maximum application rate of filter cake for spreading on agricultural land in NE England. For instance, if soil density and depth (plough layer) are 1.2 g/cm^3 and 30 cm respectively, then the application rate of filter cake will be 3.1%.

2.5.4. Quantitative models

2.5.4.1. GHG emissions from activities before the production of filter cake.

Scot Bros Ltd uses 114,285.71 L of fuel (white diesel) per month just for vehicles that collect construction waste and transport it to the site and for loading before the production of filter cake. Scott Bros vehicles include loading shovels, excavators, dozers, tippers, grab wagons, low loaders, skip wagons and hook loader wagons. Based on data from the Department for Business, Energy and Industrial Strategy. (2022a), the CO_2 emissions per 1 L of white diesel amount to 2.68 kg CO_{2eq}. We assume that the total CO_2 emissions produced as a result of collecting waste materials, transporting them from the construction site to Scott Bros Ltd, and loading them before filter cake production is equal to the total amount of fuel used per year multiplied by the CO_2 emission factor.

2.5.4.2. GHG emissions from the production of filter cake.

The filter cake production facility typically has a production capacity of 250,000 tonnes per year. The main sources of GHG emissions from machine operations are fossil fuel consumption and electricity. Scott Bros Ltd uses white diesel in machine operations for filter cake production. Eq. (6) illustrates the GHG emission calculation procedure for equipment, depending on fuel type (Sandanayake et al., 2022):

$$(E_{eq})ff = \sum E_{ff} \times F_{ff}(1 + \propto) \times h \tag{6}$$

where $(E_{eq})_{ff}$ is greenhouse gas emissions from the operating machine in $kgCO_{2eq}/m^3$, E_{ff} is the GHG emission factor for fossil fuel type (white diesel) in $kgCO_{2eq}/L$, F_{ff} is the fuel consumption of the machine in litre/hour, and h is an hour of usage. Idle time, denoted by $\propto$, refers to the time waiting to use specific equipment or, in other words, a machine's non-productive time spent on maintenance or stoppages during working hours (Paula et al., 2022).

2.5.4.3. GHG emissions from loading.

We assume that the CO_2 emission factor is 2.69 kg/L and the fuel consumption for a front loader is 88.2 L for a 9-h working per day, according to Sun and Park. (2020). Therefore, the CO_2 emissions of the front loader are calculated based on Eq. (7):

$$CO_2 \text{ emissions of the front loader } (kgCO_{2eq}/m^3) = CO_2 \text{ emission factor } (kg/L) \times \text{fuel consumption } (L) \tag{7}$$

2.5.4.4. GHG emissions from transportation.

The amount of fuel the vehicle uses and the distance it travels both affect the GHG emissions emitted. To calculate GHG emissions from transportation, Eq. (8) is used. An articulated vehicle weighing >33t has been selected to transport the amount of filter cake needed for specific destinations. The articulated vehicle that has been selected can emit the minimum amount of CO_2 compared to other types of transportation (Sandanayake et al., 2022).

$$(E_t)_Z = \sum E_z \times d_t \times (w_t + w) \tag{8}$$

where $(E_t)_z$ is the GHG emissions from transport vehicle 't' for fuel type 'z' in $kgCO_{2eq}/m^3$, E_z is the GHG emission factor in $kgCO_{2eq}$/ton-km, dt is the distance travelled in km, w is the material weight in tonnes, and wt is the dead weight of vehicle t in tonnes.

2.5.4.5. GHG emissions from spreading.

We assume that the CO_2 emission factor is 0.777 kg/L for a conventional lime spreader according to Lefebvre et al. (2019). We also assume that its fuel consumption is 135 L for a 9-h working per day. Therefore, the CO_2 emissions of the spreader is calculated based on Eq. (7).

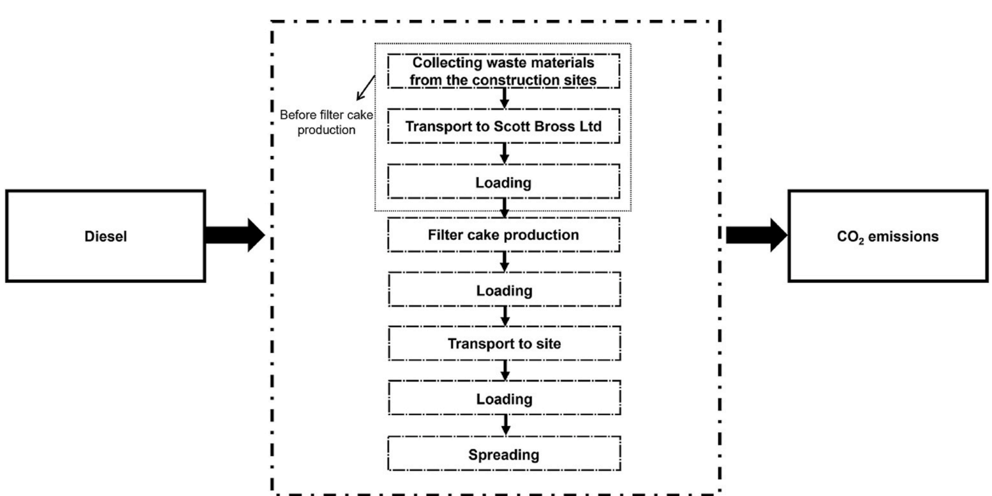

Fig. 3. System boundaries for collection, production, transportation, and spreading of filter cake.

2.5.5. Impact assessment

Impact assessments have been performed for all sources of CO_2 emissions. Other impacts such as human toxicity and freshwater eco-toxicity have been ignored due to their minor contribution to emissions in terms of greenhouse gases and other factors that affect human health, since CO_2 contributes the highest amounts of emissions and causes the most serious environmental issues and illnesses in terms of human health. Moreover, in this study, soil reactions and crop productivity have been ignored due to the negligible environmental problems they can cause, and the major focus is on the primary sources of CO_2 emissions.

3. Results and discussion

3.1. CO_2 sequestration potential of waste clay

The difference between the CO_2 sequestration potentials of filter cake through MC and EW is 0.13 CO_{2eq}/t. This means that one tonne of filter cake can remove 0.16t CO_{2eq} through MC and 0.29 CO_{2eq} through enhanced weathering. A similar case study performed in Sao Paulo, Brazil (Lefebvre et al., 2019) chose basalt rocks as the material for MC and enhanced weathering, and the results showed that the basalt rocks could capture 0.125 and 0.225 tonnes of CO_2 respectively per tonne of basalt which is 0.035 and 0.065 lower than the sequestration potentials for filter cake. Assuming a spreading rate of 11.2 tonnes of filter cake per hectare based on the availability of filter cake for spreading on agricultural land in NE England, the CO_2 sequestration potential through mineral carbonation and enhanced weathering would be 40,000 and 72, 500 tonnes of CO_{2eq} per year, respectively. Furthermore, if they continue this process until 2050 to cover all agricultural land in NE England, the total CO_2 sequestration potential through mineral carbonation and enhanced weathering would amount to 1,040,000 and 1,885,000 tonnes of CO_{2eq} (1.04 and 1.89 Mt CO_{2eq}). Fig. 4 Fig. 4 illustrates the CO2 sequestration potential of MC and EW for one year and over 26 years of applying filter cake to cover all agricultural land in NE England by 2050. Amounts of CO_2 sequestration through MC and EW were 40,000 and 725,000 tonnes CO_{2eq} per year respectively, which over the entire duration of the project would reach 1.04 and 1.89 Mt CO_{2eq} respectively by 2050.

3.2. CO_2 emission impact assessment

CO_2 emissions for all processes involved in the application of filter cake on agricultural land in NE England were calculated and are shown in Fig. 5. The results show that the highest amount of CO_2 emissions produced before filter cake production were due to the three processes: the collection of waste materials; transporting them from the construction site to Scott Bros Ltd; and loading them for filter cake production. Also, within these processes, the fleet of vehicles deployed require large volumes of fuel. Moreover, the amount of CO_2 emissions from the massive fuel consumption in filter cake production will be 3096.7 tonnes of CO_{2eq} per year, which is equivalent to 0.081 Mt of CO_{2eq} until 2050. The CO_2 emissions in the transportation process during the application of MC and EW mainly depend on the types of vehicles used and the distance travelled (Lefebvre et al., 2019; Sandanayake et al., 2022). In a previous study, transportation emissions were considered to be the main source of the production of CO_2 (Lefebvre et al., 2019). However, due to the use of articulated >33t vehicles and the average distance travelled from the filter cake production site to the agricultural land(65 km), transportation in our study was ranked as only the third highest activity in emitting 2873.83 tonnes of CO_{2eq} per year and 0.075 Mt of CO_{2eq} until 2050, while the loading and spreading processes contributed far smaller amounts of CO_2 emissions.

3.3. Effect of particle size on weathering rate

The objective of rock comminution in EW is to attain the smallest possible particle size for optimal weathering rates (Rinder and von Hagke, 2021). However, the process of crushing and grinding rocks consumes significant amounts of energy. Consequently, it is crucial when choosing machinery to take into account the energy requirements for comminution as well as factors such as crushing rates, reduction ratios, and particle size acceptance (Feng and Hicks, 2023). Moreover, the energy requirements for EW comminution can range from 10 to 316 kWh t^{-1} (Renforth, 2012). Previous research suggests that the essential range of waste particle size for MC and EW is between 10 and 20 μm in diameter (Köhler et al., 2010; Moosdorf et al., 2014; Beerling et al., 2018). According to Hangx and Spiers (2009), the energy needed to produce 10 μm particles is approximately 180 kWh t^{-1} (Hangx and Spiers, 2009). The grinding process requires considerable levels of energy consumption that affect the total sequestration potential of MC and EW (Orumwense and Forssberg, 1992), and hence this is the main drawback in applying EW technology. The average particle size of filter cake produced in this study is below 2 mm, and so energy consumption is reduced by avoiding the need for a further grinding process.

According to Strefler et al. (2018), the weathering rate of fine particles from basalt rocks with a diameter of 5 mm under normal soil conditions, a pH of 7 and at 25 °C results in the dissolution of particles at a rate of 0.021% within one year. However, factors such as soil type, fertilisation, vegetation, fungi and climate conditions were ignored in generating this hypothetical weathering rate (Harley and Gilkes, 2000;

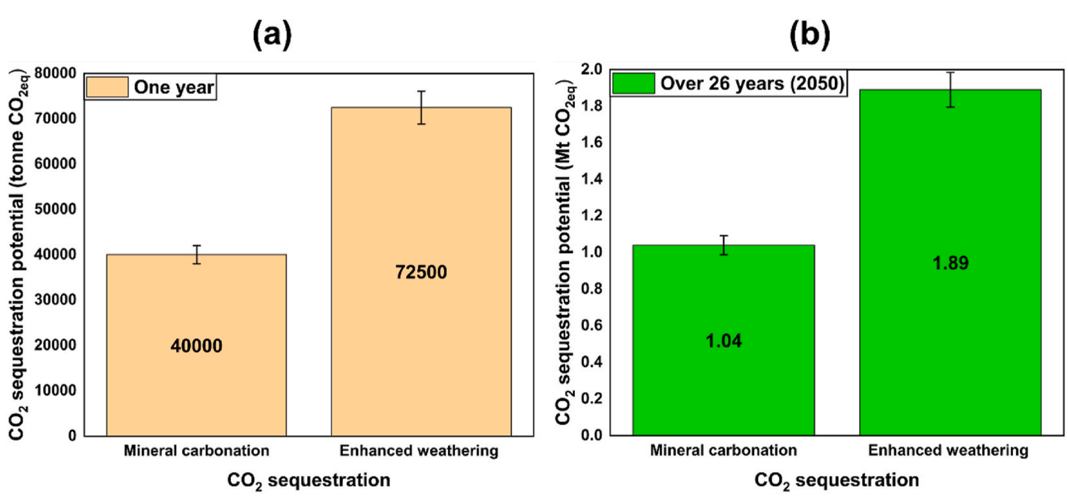

Fig. 4. CO_2 sequestration potential for a) one year and b) over 26 years until 2050 through MC and EW (note: error bars are standard error with n = 3).

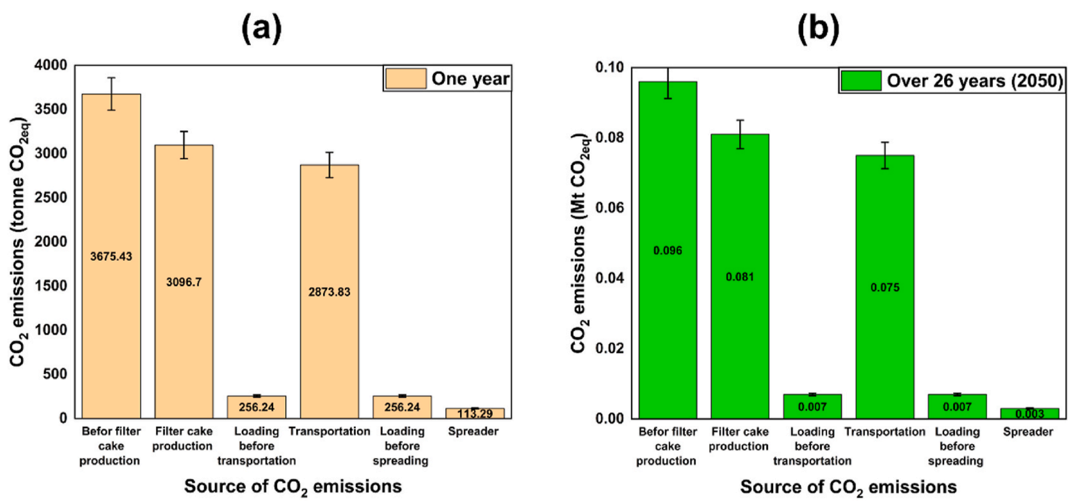

Fig. 5. CO_2 emissions source for: a) one year; b) over 26 years until 2050 (note: error bars are standard error with n = 3).

Beaulieu et al., 2010; Opolot and Finke, 2015). The accurate determination of weathering rate without taking samples from real-world fields is almost impossible given that the presence of vegetation, fungi and acidic soils plays a crucial role in weathering. However, the weathering rate of filter cake may be faster than 0.021% due to its fine particles and the soil conditions in the UK (Manning and Renforth, 2013).

3.4. Net CO_2 sequestration

The production of CO_2 emissions throughout the process of applying filter cake to the agricultural land is calculated to be 1027.73 tonnes per year and a total of 0.27 Mt of CO_{2eq} until 2050. Meanwhile, the net CO_2 sequestration potential for EW was greater than that of MC by almost 32,500 tonnes of CO_{2eq} sequestration per year and 0.85 Mt of CO_{2eq} until 2050. Fig. 6 demonstrates the application of filter cake from 2024 until 2050 with a rate of 11.2 t/ha, giving total CO_2 emissions of 0.027 Mt CO_{2eq}. On the other hand, the EW potential over the period of 26 years will be 1.89 Mt CO2eq. Subtracting the total CO_2 emissions from the net CO_2 sequestration potential (EW) then gives the net CO_2 sequestration potential, which is 1.62 Mt CO_{2eq}.

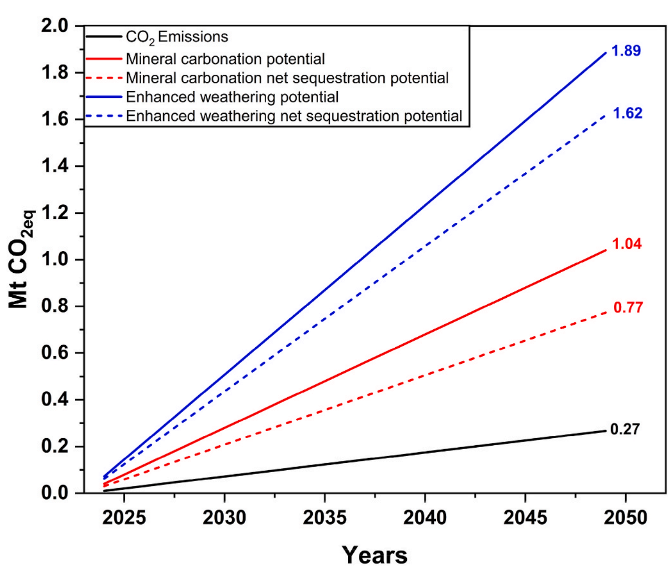

Fig. 6. Net CO_2 sequestration potential annually and cumulatively over 26 years until 2050 through MC and enhanced weathering. The dotted lines represent the net sequestration potentials resulted from subtracting CO_2 emissions and CO_2 sequestration potential for each process.

Table 2 illustrates the potential net sequestration of the NE England land with an application rate of 11 t/ha, compared with the reported total emissions of NE England, England, and the UK in 2020 (Department for Business, Energy & Industrial Strategy, 2022b). The table shows that the application of clay waste in the form of filter cake has the potential to capture about 12.46% of the total CO_2 emitted in NE England, which is equivalent to the removal of 0.53% of the UK's total emissions in one year.

4. Conclusions

In this work a process-based LCA has been conducted of the CO_2 sequestration potential of waste clay in the form of filter cake for MC and EW in agricultural land in NE England. Our findings offer valuable insights into the potential of this approach and its implications for the development and adoption of cleaner production technologies in the agricultural sector. For the sequestration potential of NE England and with an application rate of 11.2 t/ha, the deployment of waste clay could capture 0.77 to 1.62 Mt CO_{2eq} for MC and EW respectively on all of its 580,000 ha. This substantial carbon capture potential not only addresses the pressing need for carbon emissions reduction but also aligns with the broader goals of cleaner and more sustainable production practices. Moreover, one of the advantages of filter cake is that there is no need for a comminution and grinding facility to be installed, since the filter cake is produced as fine particles with a diameter below 2 mm. This leads to a reduction in energy consumption, and hence the total calculated CO_2 emissions over 26 years reached only 0.27 Mt CO_{2eq}. This remarkable reduction in energy-related emissions underscores the synergy between waste utilisation and cleaner production technologies, making it a compelling strategy for carbon sequestration. Additionally, the application of filter cake for CO_2 sequestration carries implications for waste management and the circular economy. By repurposing filter cake, this

Table 2
Net CO_2 sequestration potential of MC and EW in NE England in comparison to total CO_2 emissions in NE England, England, and the UK in 2020 (Department for Business, Energy & Industrial Strategy, 2022b).

	CO_2 emissions in 2020 (Mt CO_{2eq})	Net sequestration potential	
		MC	EW
		0.77 Mt CO_{2eq}	1.62 Mt CO_{2eq}
NE England	13	5.92%	12.46%
England	246	0.31%	0.66%
UK	306	0.25%	0.53%

approach can substantially reduce the generation of non-hazardous construction and demolition waste in England, contributing to a 6.25% annual reduction. This outcome aligns with circular economy principles, emphasising the efficient use of resources and the reduction of waste. While our study provides promising results regarding the use of waste clay on agricultural land in terms of locking away atmospheric CO2, it also highlights the importance of ongoing research and development. To fully realise the potential of this technology and its integration into cleaner production practices, further investigation is needed, particularly at the field level. Robust monitoring systems are essential to assess the impact of filter cake on soil properties, including soil pore/grain size, waterlogging, and vegetable growth.

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CRediT authorship contribution statement

Mardin Abdalqadir: Conceptualization, Conception and design of study, Funding acquisition, Acquisition of data, Formal analysis, Analysis and/or interpretation of data, Writing – original draft, Drafting the manuscript, Revising the manuscript critically for important intellectual content, Approval of the version of the manuscript to be published. **Sina Rezaei Gomari:** Conceptualization, Conception and design of study, Formal analysis, Analysis and/or interpretation of data, Writing – original draft, Drafting the manuscript, Revising the manuscript critically for important intellectual content, Supervision, Approval of the version of the manuscript to be published. **David Hughes:** Writing – original draft, Drafting the manuscript, Revising the manuscript critically for important intellectual content, Approval of the version of the manuscript to be published. **Ahmed Sidiq:** Funding acquisition, Acquisition of data, Formal analysis, Analysis and/or interpretation of data, Approval of the version of the manuscript to be published. **Feysal Shifa:** Data curation, Data source, Approval of the version of the manuscript to be published.

Declaration of competing interest

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

Data availability

The data that has been used is confidential.

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