Citation for published version:
Ntimugura, F, Vinai, R, Harper, AB & Walker, P 2021, 'Environmental performance of miscanthus-lime lightweight concrete using life cycle assessment: Application in external wall assemblies', *Sustainable Materials and Technologies*, vol. 28, e00253. https://doi.org/10.1016/j.susmat.2021.e00253

DOI:
10.1016/j.susmat.2021.e00253

Publication date:
2021

Document Version
Peer reviewed version

Link to publication

Environmental performance of miscanthus lightweight concrete using life cycle assessment: impact of binder type, binder content and application in wall assemblies

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Highlights:

- Environmental effects of miscanthus lightweight blocks were determined using LCA
- The use miscanthus shives provides environmental benefits due to high biogenic carbon capture
- Miscanthus-lime lightweight blocks can store 216 kg CO_2eq/m^3 over 100-year life cycle
- A comparative LCA of wall assemblies incorporating miscanthus-lime blocks is performed

Abstract

In the current sustainable development context, bio-based building materials have become increasingly popular for their carbon capture and sequestration. Hemp-lime has been in use since 1990s and, in the context of England, miscanthus is a potential alternative perennial crop for the development of bio-based materials. This study evaluates the environmental benefits of using miscanthus shives in lightweight blocks and their potential use in wall assemblies. A detailed life cycle assessment (LCA) is carried out for miscanthus-lime blocks, and the effects of binder type and binder content are discussed. The environmental performance-based analysis shows that miscanthus blocks can store 216 kg CO_2eq/m^3 for an assumed 100-years life period. The impact analysis using CML baseline (v4.4) method has shown that 92.2% of the greenhouse gases emissions from the production of miscanthus blocks are attributable to the production of binders. A reduction of binder to aggregate ratio from 2.0 to 1.5 reduces GHG emissions by 23.5%. The use of 10wt% mineral additions can potentially stabilise blocks while having little effect on their environmental impacts. The association of miscanthus blocks with fired clay bricks allows a potential low carbon retrofitting technique for the stock of residential buildings in the UK. Timber-framed system filled with miscanthus blocks enables carbon storage of ~130 kg CO_2eq/m^2, which presents a potential carbon offsetting strategy in newbuilt dwellings. Consideration should be given to the potential negative impacts that are related to agricultural activities for the production of miscanthus shives. The largest negative environmental impact in this study was eutrophication potential; where incorporating miscanthus in a wall could potentially increase the eutrophication potential by 55.7% compared to a typical solid wall insulated with mineral wool. As a result of this study, that miscanthus-lime composites can substantially improve the environmental profile of wall assemblies and sustainability be associated with existing uninsulated masonry walls or timber- framed new-built houses.

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Commented [NF3R2]: ok

Commented [HA4]: This is a little vague – do you mean the environments of the buildings? Or ‘the environment’ as in nature etc.

Commented [NF5R4]: 10% additions contribute little in varying the environmental impacts associated with the production of blocks

Commented [HA6]: Does this mean “Combining miscanthus blocks with traditional bricks …”

Commented [NF7R6]: Yes, as in Fig. 5

Commented [HA8]: Negative storage would be an emission

Commented [NF9R8]: Corrected

Commented [HA10]: If the paper is about Miscanthus bricks this seems a little out of place

Commented [NF11R10]: Timber frame is filled with miscanthus blocks

Keywords: bio-based building materials, environmental impact, thermal insulation, carbon capture, miscanthus-lime.

1. Introduction

Buildings consume large quantities of energy and it is generally agreed that reducing the energy consumption of buildings is a necessary step in reducing the global energy consumptions and associated greenhouse gases emissions. In the UK, considerable energy use and environmental effects are attributed to space heating in residential buildings [1]. Considering the actual global environmental challenges, the European governments and the UK adopted policies toward a more sustainable built environment by regulating the energy efficiency of buildings. The latter requires sustainable materials and construction systems be made accessible to the construction industry. As result of this growing awareness of sustainability concerns, environmentally friendly building materials that have potential applications in residential buildings have emerged, and among the most promising are lightweight bio-based building materials. Residential buildings constitute more than 3/4 of the energy consumption allotted to the built environment in the UK, for a total of ~ 30% of national energy consumption. Considering the estimated 3.2 million residential buildings in the UK, even the smallest contributions on impacts and consumption of resources would be significant at a national scale. In fact, the UK performance in reducing emissions over the second carbon budget period estimated insulated cavity walls to be 0.1/0.8 million installations and 0/0.1 million installations for solid walls and 0/1.2 million installations for lofts insulations.

Commented [HA12]: You may find some useful information in this report, to put UK buildings in context of need to reduce emissions in th UK https://royalsociety.org/topics-policy/projects/greenhouse-gas-removal/

Commented [NF13R12]: Thanks

Commented [HA14]: These are important numbers for justifying your focus, I'd move them up earlier in the introduction.

Commented [NF15R14]: Move up

In general, conventional wall infilling materials exhibit poor to average heat insulating properties. Lightweight materials, such as glass wool, mineral wool, expanded polystyrene and extruded polystyrene, are required to improve resistance to the passage of heat [2]. A recent cradle to gate life cycle assessment of conventional insulation materials reports values of global warming potential (GWP100) in the range of 3.25-7.8 kgCO$_2$eq for ~ 0.6-1.0 kg of materials, and a consumption of 73-104 MJ for their production [3]. These materials exhibit high environmental impacts and their ecological efficiency is being called into question [4]. This compels to assess the appropriateness of novel insulation materials, based on their local availability, renewability, low-energy processing techniques, and acceptable levels of insulation [5]. Bio-based fibres and particles constitute a particular class of materials with such potentials for applications in buildings [6], in particular due to their inherent honeycomb porous structure [7]. In addition to low-energy processing associated with their manufacturing, their biogenic carbon capture and storage is a desirable trait in the context on sustainable, low-energy and affordable building envelopes [8].

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Commented [NF17R16]: The functional unit was calculated as the mass of materials that provide a unit thermal resistance. That mass varied between 0.59 – 1.02 kg.

A high number of studies on the thermal performance and sustainability of buildings suggests a design-oriented optimisation and operational energy reduction techniques. While the effectiveness of the latter is unquestionable, the embodied energy associated to these techniques remains relatively high. In a typical UK residential house, the embodied carbon represents 20-26% of the total life cycle carbon, with a potential increase of 1-13% associated with regulatory improvements of the thermal performance [9]. In residential and commercial buildings, the embodied energy was found to contribute to 22% and 26% of the total life cycle energy, respectively [10]. Over the past few decades, the building fabrics have thermally improved to meet the ever-stringent building regulation requirements, leading to increasingly low thermal transmittance (U-values) and as a consequence, a reduction of heat losses through the newbuilt envelopes. Furthermore, considering the new trends in the design of most effective houses adopting the passive designs, the embodied energy can account for up to 50% of the total energy consumption [11].

Gonzalez and Navarro have shown that a careful choice of materials can reduce the global warming potential by up to 30% in the context of terraced houses in Spain [12]. This confirms that the use of sustainable materials can be a point of focus for action to reduce the CO_2 emissions. In the particular context of restoration and preservation of historic buildings, the actual air-permeable materials and the need then to prevent impermeable layers in the structure of walls precludes the use of closed-foam and plastic-based insulants [13]. Their lack of hygroscopic properties prevents beneficial vapour pressure buffering and hence increases the risks of surface and interstitial condensation. In these particular conditions, vapour permeable bio-based building materials offer an unrivaled solution for the restoration works [14]. The aforementioned remarks made by explain the potential use of low-energy biomaterials as alternatives to standard commonplace energy-intensive insulating materials.

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Commented [NF19R18]: Indeed, thanks

Ideally, building with bio-based materials brings about the most sustainable dwellings with acceptable thermal performance and high level of indoor air quality and comfort. Pierquet et al. [15] investigated the thermal performance and embodied energy of eleven wall systems used in the US. The authors covered a whole range of construction materials ranging from conventional concrete blocks-based wall, improved non-conventional aerated autoclaved concrete walls and straw bale walls. The authors reported that non-renewable materials (concrete, steel, synthetic foams) have the lowest long-term energy performance. The LCA of UK detached, semi-detached and terraced dwellings was conducted using GaBi software and a combination of Ecoinvent / GaBi databases and available literature data [16]. The authors estimated the GWP of 132 million tonnes (Mt) CO_2 eq. per year, leading to a cumulative 6.6 billion tonnes over 50 years, at the house sector level.

A recent life cycle assessment of bio-based building materials for insulation of walls in buildings reports a potential opportunity for CO_2 capture and storage in the UK. Ip and Miller reported a carbon storage of -36.08 $kgCO_2eq./m^2$ of hemp concrete walls [17]. In a similar French study, Boutin et al. [18] investigated the environmental performance of hemp concrete using a detailed LCA model and similar carbon capture and storage figures ~ -35.53 $kgCO_2eq./m^2$ were reported. These materials benefit from the biogenic carbon capture of hemp and carbonation of lime binder. Arrigoni et al. conducted assessment of the role of carbonation, proportion of components and transportation in LCA results of hemp concrete blocks was carried out by [19]. The authors experimentally determined the carbonation of hempcrete blocks using x-ray powder diffractions (XRD) and integrated the obtained quantitative results in the LCA model. After 240 days of curing, the estimated binder carbonation was only 9-12 g per kg of binder. Nevertheless, negative net carbon emissions ~ -12.09 $kgCO^2/m^2$ of wall were reported. Even though the reported figures remain lower than those previously reported, these results confirmed that hemp blocks could act as carbon sinks even with limited contribution of binder carbonation. While the rate of carbonation of lime-based binders inside bio-based composites remains arguable, Arehart et al. proposed a theoretical model for carbon storage and sequestration of hempcrete [20]. The authors estimated the carbonation of lime-based binder between 18.5% and 38.4% with a minimum CO_2 storage potential of -16 $kgCO_2eq./m^2$ of a hemp concrete wall.

Hemp-based building materials have been successful in France due in part to high production of hemp fibres and shives. In the context of the UK, hemp shives production remains limited, and miscanthus is proposed as an alternative source of bio-aggregates. In fact, the UK Committee on Climate Change suggests expanding energy crops by 23 000 ha/year, including miscanthus, and estimates carbon reductions of ~11 $MtCO_2$ per year from harvested biomass; spurring further research and innovation around the use of miscanthus fibres and composites for buildings [21]. In addition, the CO_2 mitigation potential associated with miscanthus farming was proposed to be considered in the greening measures of the EU Common Agricultural policy regulations 2014-2020 [22]. Ben Fradj et al. insisted on the potential of miscanthus in bio-based sectors including the development of building materials [23]. Even though miscanthus is suitable for use in lightweight concretes [24], only limited literature covers the potential of miscanthus concretes [25]–[27]. This study proposes an environmental assessment of miscanthus lightweight blocks in the UK, and their potential application in conventional wall systems.

Commented [HA20]: Is this the same as miscanthus??

Commented [NF21R20]: Yes, I will keep miscanthus for uniformity

Low energy designs involve either the investment in insulation of building's fabric, glazing and the improved airtightness and ventilation strategy. These strategies could be eventually applied using insulating materials that are environmentally friendly, capable of reducing both the operational and embodied energy of dwellings. This study assesses the environmental performance of such a material produced using local miscanthus shiv. The research presents a comparative analysis of wall assembly systems made of typical standard materials used in the UK against those made of the innovative miscanthus-lime composites. The environmental performance of miscanthus blocks wall is compared to that of the existing walling systems, to respond to the reluctance of the construction industry and promote the widespread adoption of miscanthus-based building materials in the UK.

2. System description and inventory data

In this section, the goal and scope, description of systems, materials and functional unit, the implementation and end-of-life scenarios are discussed. The environmental impacts are calculated for miscanthus concrete blocks and sensitivity analysis is conducted to investigate the effect of the type of binder, binder content and transport distances. In the end, the environmental impact indicators are analysed for wall assemblies that include miscanthus blocks and compared to a standard solid wall insulated with a layer of mineral wool.

2.1 Scope and description of system boundaries

The aim of this study is to evaluate the environmental performance of miscanthus lightweight concrete blocks and to assess its potential impact on the environmental profile of typical wall construction systems used in the UK, using a comparative analysis. The comparative LCA of wall systems was performed using the concept of life cycle analysis of building materials and component combinations (LCA-BMCC) as defined in [28]. The assessments are conducted from the production of raw materials to waste disposal/recycling considering flows of materials and energy in separate subsystems (agricultural, processing and construction subsystems). An attributional life cycle approach (ALCA) that considers average data for all flows of different processes was used and results discussed at all levels of the overall system.

The framework, principles, and guidelines for life cycle assessments were followed as described within the International Organisation for Standardisation standards, ISO 14040 and ISO 14044. This paper presents an assessment of environmental performance of miscanthus concrete and wall assemblies, from miscanthus grown in South West England. The overall system boundaries are presented in Fig. 1. The elements of the system in Fig. 1 were subdivided in subsystems as follows: (a) Miscanthus is grown at Lower Marsh farm in Taunton (Somerset), where elementary flows from soil preparation to miscanthus stems baling are considered. Miscanthus bales are then transported to factory site, chopped, dedusted and packaged. The details of this agricultural subsystem are presented in Fig. 2. (b) The chopped miscanthus shives are transported to the miscanthus blocks factory where they are processed and mixed with binder to produce blocks. Fig. 3. shows the details of the block production subsystem. (c) The produced blocks are then transported to the building site where they are assembled and mounted in wall systems with clay bricks and concrete blocks. Fig. 4 illustrates the itinerary through processes of the aforementioned subsystems, from field to miscanthus blocks. A typical application of bio-based concrete in a traditional masonry wall assembly is shown in Fig. 5.

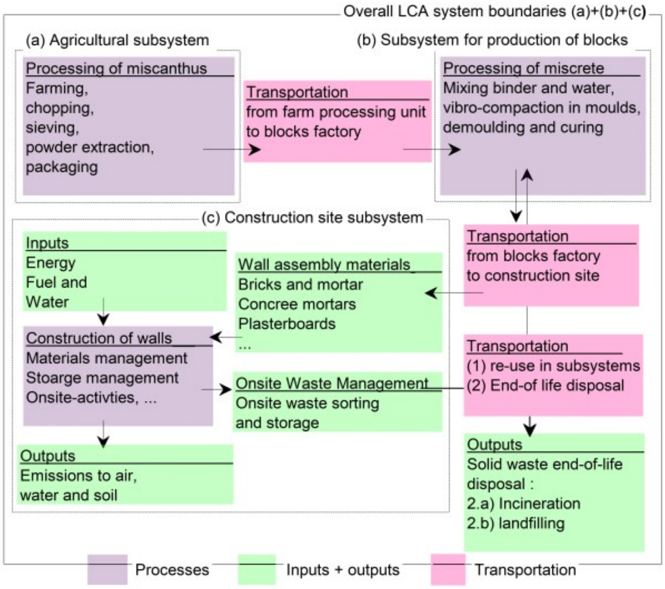

Fig. 1. Life cycle boundaries of miscanthus concrete walls

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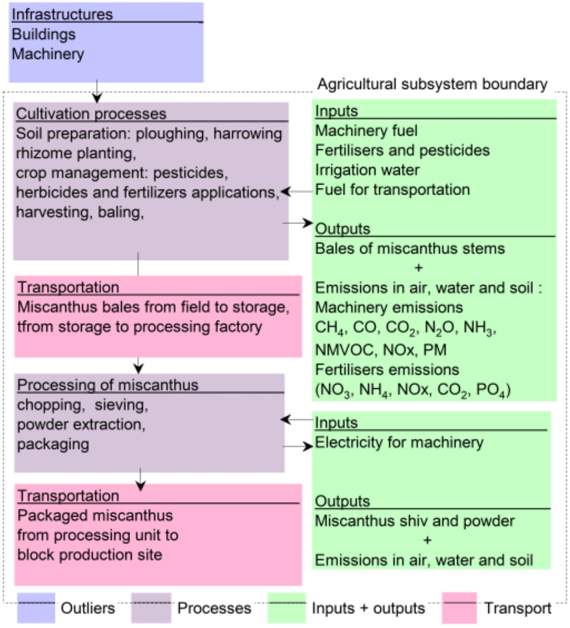

Fig 2. The boundaries of the agricultural subsystem for the production of miscanthus shives

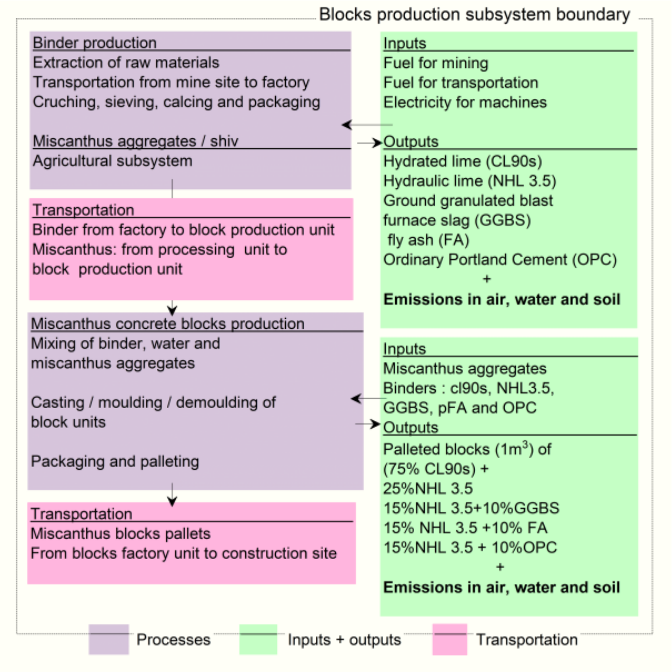

Fig. 3. The subsystem boundaries for the production of miscanthus concrete blocks. (Reduce the width of the image to fit 140 mm)

Fig. 4. Miscanthus block production: a) miscanthus field at Lower Marsh farm in Taunton in September, b) senesced miscanthus canes in January, c) stocks of baled miscanthus canes, d) pile of miscanthus shiv e) typical miscanthus concrete blocks

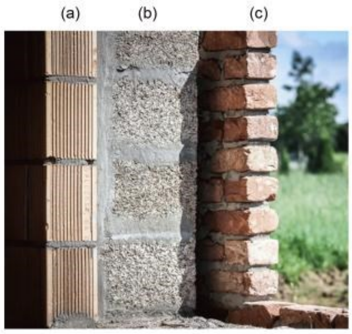

Fig. 5. Illustration of a typical bio-based building cavity wall assembly made of hemp concrete. (a) load bearing fired clay blocks, (b) hemp concrete blocks and (c) outer leaf layer of bricks (Courtesy of Isohemp, 2020).

Commented [HA24]: What is in each layer?

2.2 Inventory method and data collection

2.2.1 Cultivation of miscanthus and production of shiv

There are a variety of agricultural practices for miscanthus farming in the UK. However, the Department for Environment, Food and Rural Affairs (DEFRA) has set a guide of best practices that are followed by most farmers to grow miscanthus. These practices were considered in addition to farming and crop management techniques used at Lower Marsh farm in Taunton. The cultivation of miscanthus consists of several steps: field preparation for planting, rhizome planting, crop management and weed control all happening during the crop establishment first year. The annual operations consist in harvesting, baling, transportation from field to the storage area and shredding/chopping of miscanthus canes. The average diesel consumption of agricultural machinery for all activities from ploughing to baling were collected during farm visit in Taunton. The total amount of diesel consumption was estimated at 88.5 liters/ha as detailed in appendix A of supplementary data. The production and supply of miscanthus rhizomes were not considered in the assessments. The impact of the agricultural subsystem processes was calculated on the basis of the performance of agricultural machinery (operation, power rate of the used machinery (hp), productivity (hours/ha), diesel consumption (L/ha) and emissions. There are no fertilisers applied in the farming of miscanthus at Lower Marsh farm. The application of glyphosate (3kg/ha) was considered during the establishment year for weed control. Although a rather comprehensive analysis of processes was conducted, the life cycle assessments involving agricultural systems remain complex as they require the analysis of specific pedoclimatic conditions, farming management practices and technologies, specific characteristics of perennial crops and any crop rotation [29]. Such element are outside the scope of the present study.

Bio-based building materials benefit from the absorption of atmospheric CO_2 during the agricultural growth of crops. However, the quantification of biogenic carbon capture and sequestration of crops remains a controversial subject mainly due to the complexity of the soil-air-plant system [30]. In a study on the environmental costs of growing miscanthus in the UK [31], in addition to biogenic capture of CO_2, the soil organic capture (SOC) was estimated at ~ 0.98 tonnes of carbon /ha/year . However, soil carbon capture was considered out of scope of this study. Considering an average biomass yield rate of 10 tonnes /ha, the weight of CO_2 capture was stoichiometrically calculated from the equation 1.

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Commented [NF26R25]: Right, thanks

$$Q_{CO2} = C_c C_f (\rho_w V_w / 1 + w) \qquad \text{(Eq.1)}$$

Where Q_{CO2} is the captured carbon dioxide at the moisture w (%), C_c is the molar mass ratio of carbon dioxide to carbon (44/12), C_f the carbon fraction of the biomass (dry), density of the biomass at w% moisture, V_w volume of the biomass at the moisture w%. This method conforms to EN 26449 and is recommended by RICS was adopted for this study. The application of the equation 1 gives a value of ~ 1.75 kg CO_2/ kg of miscanthus. This value of was allocated in the LCA model as negative CO_2 emissions for the production of miscanthus. An average annual yield of 10 t/ha was considered, and the mass allocation method was used for the products of miscanthus canes shredding: 80% of shiv, 10% of fibres and 10% of dust. The production of miscanthus shiv is performed in four major steps including bales opening, decortication of stems, separation of shivs and fibres, and air-dedusting. This production line includes a tub grinder and a hammermill with the consumption power rate of 220 kw/h for a processing capacity of 3.6 tonnes per hour.

2.2.2 Mineral binders and production of miscanthus blocks

Prevalent binder formulations used with bio-aggregates are widely reported in literature and consist of hydrated lime, hydraulic lime and pozzolans. The binders used in the production of miscanthus concrete were a binary blend of hydrated lime (CL90s) and natural hydraulic lime (NHL3.5). Additional mineral pozzolans were considered including ground granulated blast furnace slag (GGBS), fly ash (FA) and Ordinary Portland Cement (OPC). Hydrated lime, hydraulic lime and cement were sourced from Blue Circle. A wide number of lime and cement factories are available within 200 km distance around Somerset. Ground granulated blast furnace slag (GGBS) is a by-product of the iron production process and was sourced from Ecocem (Ireland). Its transportation distance was estimated at 346 miles with 78 miles of ferry across the Irish sea. Fly ash (FA) is a waste material produced during the combustion process in coal-fired power stations. It is a high calcium material and presents high reactivity with free portlandite. The PFA used here was sourced from power plant in North Yorkshire (Drax Power Station) within an average distance estimated at 280 miles. The transportation of mineral binders was performed by road and assumed within a 90% loaded 24-ton truck for specific distances from suppliers.

The delivery of materials to the factory site for the production of miscanthus blocks was considered in 24 tonnes freight lorries within distances of 100 km for miscanthus shiv and 200 km for lime. The binder and miscanthus shivs were mixed and cast using typical concrete blocks production line that consumes 3.0 kwh for each m^3 of mixture. The produced miscanthus blocks were subsequently cured on shelves and allowed to harden in indoor conditions with temperature and humidity conditions ~20ºC and 50%RH. After curing, miscanthus blocks were packaged and loaded on wood pallets to be transported to the construction site. The packaging was considered using polyethylene films (100g /m^2) and palleting (1pallet per m^3), and the transportation from factory to blocks production unit at a distance of 100 km. On the construction site Miscanthus concrete blocks were assembled with other building materials to form wall structures. The use phase of construction materials was considered once blocks were delivered on the building site. Different methods have been used to quantify the absorption of CO_2 of lime-based binders in lightweight hemp-based materials. Boutin et al. have considered 0.249 kg CO_2/ kg binder [18], while Ip and Miller considered 0.571 kg CO_2/ kg binder [32]. Pretot et al. [33] and Arrigoni et al. [34] estimated the CO_2 uptake of hemp concretes at 0.325 and 0.462 kg CO_2/ kg binder, respectively. In this study, the carbonation of lime-based binders was considered for hydraulic and hydrated lime at 0.514 kg CO_2 per kg lime, corresponding to the reabsorption of 90% of the CO_2 emitted during the calcination of limestone (0.517 kg CO_2/kg limestone) [35]. The assemblage of construction materials on the construction site require a set of small tools and human energy that were not accounted for in the life cycle model. The production and supply of other construction materials are considered. The end of life considers waste treatment and landfilling.

3. Methods

3.1Functional unit

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Commented [NF28R27]: Section re-organised

The building regulation codes specify requirements on heat transfer, air leakage and moisture condensation control in building fabrics and wall systems separating outdoor and indoor spaces. In this study, the functional unit of wall systems was chosen to comply with the energy efficiency requirements of the UK building regulations (Part L) [36]. To compare components, both walling systems equipped with conventional insulating materials and those with miscanthus concrete were set to have comparable insulation properties. The functional unit was defined as one square meter of wall and the thickness of elements adjusted to have the same thermal transmittance value (U-value) of ~ 0.30 W/m^2K as prescribed in the building regulations standard in the UK (Conservation of fuel and power, document L). In this study, the wall systems were adapted from common practices in the construction of residential buildings in the south west of England were considered from the Local Authority Building Control (LABC)[37]. It was assumed that the wall systems have the same application and that the insulating role is the most prominent. Other properties such as mechanical, moisture sensitivity and durability were not considered. The thermal conductivity of miscanthus concrete was assumed similar to that of hemp concrete with comparable final density values (~400 kg/m^3). Using the linear model proposed by Cérézo [38], the final thermal conductivity (λ_d) was obtained from density ($\lambda_d = 0.0002\rho + 0.0194$). This model, agrees with experimental values reported by Nguyen, considering the anisotropy of hemp concretes [39].

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Commented [NF30R29]: Yes, the reference has been added

Commented [HA31]: Can you define U-value when it first occurs in the Introduction?

Commented [NF32R31]: U value defined in the introduction

Three scenarios of different wall assemblies were investigated. Materials making up these structures from the exterior to the interior were: (a) a traditional structural timber frame filled with miscanthus concrete and cladded with 9 mm fibre cement tiles, 12.5 mm of OSB sheathing board, 400 mm of miscanthus concrete and 12.5 mm of plaster board (WSA-Ti). (b) A cavity wall made of a 102 mm brick layer, 50 mm air cavity, a breather membrane, 9 mm of OSB sheathing board, 250 mm of miscanthus concrete, a vapour control layer and 12.5 mmm of plasterboard (WSA-Br) and (c) a solid wall of made of 102 mm brick layer, a breather membrane, 85 mm of rock wool, 100 mm of autoclaved aerated concrete blocks, a vapour control layer and 12.5 mm of plaster board (WSS-Min.W). The thermal properties of these materials were obtained from the environmental product declarations (EPD) of available products on the UK market and the thicknesses of the walls elements adjusted to attain an overall thermal transmittance of 0.30 W/m.K for all scenarios.

3.2 Emissions models and impact indicators

The quantification of flows in the agricultural subsystem requires data or models for fuel consumption, exhaust gases and direct emissions in air, soil, and water. There exist a wide range of available models to predict fuel consumption of farming operations. Andrianadraina et al. [40] used a combination of fuel consumption model and required for hemp farming operations and integrated them in hemp concrete LCA. In this study, fuel consumption data was acquired at Lower Marsh Farm in Taunton (UK) and complied with models in [41]. However, the emission of pollutants (CH_4, CO, CO_2, N_2O, NH_3, NMVOC, NOx, PM) (kg/ha) was modelled using the equation 2 and the obtained result integrated in the LCA model.

$$E_i = \sum_{j,t} FC_{j,t} \times EF_{i,j,t} \qquad \text{(Eq.2)}$$

Where $FC_{j,t}$ is fuel consumption of fuel type j by equipment of technology type t (L/ha) and $EF_{i,j,t}$ is the average emission factor for pollutant i, fuel type j and the equipment of technology type t.

This method is recommended in the EU and builds on the US EPA method designed to estimate off-road emissions, and it has been enacted in the UK. The used methods for the estimation of exhaust gas emissions from agricultural tractors is compliant with methodologies in [42]. Soil carbon impacts are an interesting, important, yet uncertain aspect CO_2 removal strategies [43]. The soil can sequester and store an average of 100-300 kg/ha/year depending on agricultural practices. Nakajima et al. [44] reported soil carbon sequestration of 1.96 ± 0.82 Mg C ha^{-1} $year^{-1}$ for miscanthus. However, these results are site specific and highly influenced by the climate and type, site use history and management practices. Considering the uncertainties related to the evolution of agricultural practices and site history data, soil carbon capture and storage was not considered in this study.

There exist a variety of LCA softwares including Sima Pro [45], GaBi [46], Umberto [47], Quantis [48], OpenLCA [49]. The software OpenLCA v1.7.4 developed by GreenDelta was used in conjunction with Ecoinvent 3_1 database, allowing a modular-oriented LCA in a highly flexible and opensource environment [50]. The obtained results were exported and analysed using Excel. The impact assessment method can be classified as midpoints and endpoints assessment methods. The midpoints method was chosen in this study as it restricts quantitative results at the early-stages of cause-effects chain, which limits the uncertainties associated to grouping into end-point categories. The LCIA was calculated based on CML (baseline) v 4.4-January 2015 method developed by the Institute for Environmental Sciences (CML) at the University of Leiden in the Netherland. It provides results in terms of 11 impact categories: acidification potential (Ac.P), climate change (GWP100), depletion of abiotic resources - elements, ultimate reserves (DAR-elements), depletion of abiotic resources - fossil fuels (DAR-fossils), eutrophication potential (Eu.P), freshwater aquatic ecotoxicity (FAETP), human toxicity potential (HTP), marine aquatic ecotoxicity (MAETP), ozone layer depletion potential (ODP), photochemical oxidation (Ph.O) and terrestrial ecotoxicity potential (TETP). Some assumptions and hypotheses were considered throughout the assessments:

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- The potential environmental impacts associated with the construction of agricultural buildings and manufacturing of machinery were not considered.
- Components of less than 2% of the total inventory and data of high uncertainty (wall ties, nails for wood frame, …)
- The electricity for wood frame mounting was estimated negligible and hence not considered
- The method used here is cradle to grave and the life duration of 100 years for wall systems and all their components

3.3 Results analysis and optimisation

The obtained results were normalized to the maximum values of impact categories to assess the variations within individual impact categories for all scenarios. Linear programming (LP) approach was used for purpose of comparative assessment of scenarios for the overall environmental performance considering all the 11 impact categories. The computer software LINGO 18.0 was used to solve the optimisation linear programming (LP) model [51]. An LP model (equation 3) can be described as an optimization (minimization) of a series objective functions applied to impact categories [52] : Minimize $Q_i(x)$;

$$Q_i(x) = \sum_{k=1}^{l} a_{ki}x_{ki} = a_{1i}x_{1i} + a_{2i}x_{2i} + \cdots + a_{li}x_{li} \qquad \text{(Eq.3)}$$

Where $Q_i(x)$ is the i-th objective function, a_{ki} the coefficient of the objective function and x_i the quantitative measures of outputs which is subject to constraints. In the context of LCA, the objective functions can represent the overall environmental impact where a_{ki} represents the relative contribution of a burden or impact indicator x_i [53]. In this study, the linear weighted sum method was the approach adopted to solve the problem in equation 4, and the equation 3 became: minimize $f(x)$;

$$f(x) = \sum_{k=1}^{l} \omega_k Q_k^o(x) = \omega_1 Q_1^o(x) + \omega_2 Q_2^o(x) + \cdots + \omega_l Q_l^o(x) \qquad \text{(Eq. 4)}$$

Where the $Q_k^o(x)$ is the normalized objective function of $Q_k(x)$ and ω_k represents weighting factors such as $\omega_1 + \omega_2 + \cdots + \omega_l = 1$.

4. Results and discussions

In this section, the environmental impact categories are reported for both miscanthus concrete blocks and wall assemblies scenarios. Three scenarios were considered for miscanthus blocks to investigate the sensitivity of the model and optimize the environmental performance of blocks. Scenarios of binder content investigate the effects of increasing levels of binder to aggregate mass ratios: low binder content (1.5 b/a), reference binder content (2.0 b/a), medium binder content (2.5 b/a) and high binder content (3.0 b/a). Scenarios of composition of binder blends that considers a binary binders made of 75% hydrated lime + 15% hydraulic lime (75%CL90s+15%NHL3.5) and three ternary binders based on 75% hydrated lime, 15% hydraulic lime and 10% ground granulated blast furnace slag (GGBS), fly ash (FA) or cement (OPC). These include 75%CL90s + 15%NHL3.5 + 10%GGBS/10%PFA/10%OPC. GGBS and FA are industrial wastes that are widely available in the UK, and potentially beneficial from both environmental standpoint and early age strength improvement of blocks. Last, the impact of transportation distance of binders was evaluated at three levels: low distance (100 km), reference distance (200 km) and long distance (500 km). Two extreme distances were added to assess the overall impact of transportation on impact categories: (a) very short distance (10km) and very long distance (2000 km). The details of these scenarios are shown in Table 1.

Commented [HA34]: Can you describe how this will be presented? What exactly are your impact figures showing? They are a little difficult to interpret.

Commented [NF35R34]: Thanks, I am trying to explain that we first discuss the production of miscanthus blocks before integrating these into wall structures

Commented [NF36R34]:

Table 1. Miscanthus concrete production and transportation scenarios

Scenario	Variable parameters	b/a (kg/kg)	w/b (kg/kg)	Wabs (%)	Binder type	Misc (kg/m^3)	Water (kg/m^3)	Binder (kg/m^3)	T.D. Misc (km)	T.D Binder (km)
A (R)	type of binder	2.0	0.55	120	CL90s+NHL3.5 (i)	157	348.17	315.1	100	200
B		2.0	0.55	120	CL90s+NHL3.5+GGBS (ii)	157	348.17	315.1	100	200
C		2.0	0.55	120	CL90s+NHL3.5+OPC (ii)	157	348.17	315.1	100	200
D		2.0	0.55	120	CL90s+NHL3.5+FA (ii)	157	348.17	315.1	100	200
A-1.5 kb	Binder content	1.5	0.55	120	CL90s+NHL3.5 (ii)	187	358.12	277.3	100	200
A-2.15 kb (R)		2	0.55	120	CL90s+NHL3.5 (i)	157	348.17	315.1	100	200
A-2.5 kb		2.5	0.55	120	CL90s+NHL3.5 (i)	137.14	340.8	342.86	100	200
A-3.0 kb		3	0.55	120	CL90s+NHL3.5 (i)	121.42	335.12	364.25	100	200
A-2.15kb-T1 (R)	Transport distances	2.0	0.55	120	CL90s+NHL3.5 (i)	157	348.17	315.1	100	200
A-2.15kb-T2		2.0	0.55	120	CL90s+NHL3.5 (i)	157	348.17	315.1	100	100
A-2.15kb-T3		2.0	0.55	120	CL90s+NHL3.5 (i)	157	348.17	315.1	100	50
A-2.15kb-VL		2.0	0.55	120	CL90s+NHL3.5 (i)	157	348.17	315.1	100	2000
A-2.15kb-VS		2	0.55	120	CL90s+NHL3.5 (i)	157	348.17	315.1	100	10

b/a: Binder to aggregate mass ratio; w/b: water to binder mass ratio; Wabs: Water absorption of aggregates; TD: Transportation distance; Misc: Miscanthus shiv
(i) 75% hydrated lime [CL90s] + 25% natural hydraulic lime [NHL3.5]; (ii) 75 hydrated lime [CL90s] + 15% natural hydraulic lime + 10% mineral additions
Mineral additions: (GGBS, ground granulated blast furnace slag; OPC, Ordinary Portland Cement, FA: fly ash)
(R),The base case as reference for every set of scenarios within a type of studied variable parameter

4.1 Miscanthus concrete blocks: base case results

The results are first presented for all impacts categories for miscanthus concrete base case (scenario A), followed by a description of the contribution of main phases (agricultural and miscanthus blocks factory and transportation). A detailed analysis of global warming potential of the base case is presented , followed by a sensitivity analysis of the LCA model considering the type of binder, the binder content and binder transportation distances are considered. The results from sensitivity analysis related to the type of binder and binder content were subsequently used to optimize the environmental performance of the miscanthus concrete using Linear Programming in section 4.2.2

The breakdown of GWP100 from processes related to the production of miscanthus concrete blocks base case (scenario A) is presented in Fig. 6a and b. The obtained results show that the production of binders and their transportation contribute to ~245.5 kgCO_2eq/m^3 while miscanthus aggregates absorb ~ -276 kgCO_2eq/m^3. These figures suggest that the optimization of GWP100 impact level requires mix design methods involving a reduction of binder content and an increase of miscanthus aggregate content. The overall net global warming potential of miscanthus concrete is -216 kg CO_2eq/m^3. The major contributor remains the production of binders which accounts for 167.5 and 58.9 kg CO_2eq/m^3 for CL90s and NHL3.5, respectively, for a total of 226.42 kg CO_2eq/m^3. In fact, the production of hydrated lime involves the emission of 0.75kg CO_2eq /kg of produced lime [54]. The recorded absorption of carbon dioxide was attributed to miscanthus farming corresponding due to a high absorption input of - 1.75 kg CO_2eq/kg of miscanthus shiv. The carbonation of miscanthus blocks over the life cycle contributed for - 161.9 kg CO_2eq/m^3

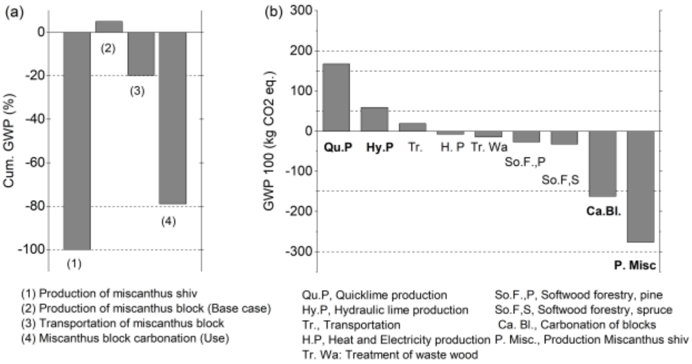

Fig. 6. Impact of miscanthus concrete, scenario A, on global warming potential (GWP100). (a) the cumulative contribution of major phases of miscanthus block life cycle. The figures show the % of embodied CO_2 after each step with - 100% corresponding to the CO_2 absorbed at the end of the miscanthus shiv production ~ -276 kg CO_2eq/m^3 and (b) the individual contribution of major processes at 1% cut-off.

Table 2. presents the recorded levels of all impact categories for miscanthus concrete base scenario A. These results are compared with literature values for for hemp concrete studies that used CML as the LCIA. Only Some impact categories were considered in these studies following the standards NF P01-010 and EN 15804:2012. Fig 7 shows the cumulative contribution of miscanthus shiv production, block casting, transportation, and use phase of miscanthus blocks to 10 impact indicators except for global warming potential which is detailed in Fig. 6. These results highlight that the production of blocks contributes for at least 60% to all impact categories except for the Eu.P (~25.7%). The greatest values of impact categories are recorded for photochemical oxidation (Ph.O), Acidification Potential (Ac.P) and ozone layer depletion (ODP), all reaching ~ 85% contribution. These are related to high-energy extraction and processing of raw materials, transportation, and their associated emissions to air, water and soil.

Table 2. Environmental impact indicators for base case of 1m^3 of miscanthus concrete (scenario A). The values were compared to literature data recalculated for 1 m3 of hemp concrete. NA (Not Available) indicates that values for these impact categories were not reported. In Arrigoni et al. the values are the minima of all scenario. The maximum values are shown in parentheses. DCB = Dichlorobenzene.

		Present study	Boutin et al.	Arrigoni et al.
Impact categories	Units	Impact category levels per m3		
TETP	kg 1,4-DCB eq.	0.572	NA	NA
Eu.P	kg PO$_4$--- eq.	0.465	NA	5.28E-02(7.06E-02)
GWP 100	kg CO$_2$ eq.	-215.63	-136.68	- 40 (-140)
Ac.P	kg SO$_2$ eq.	0.675	0.385	0.3 (0.6)
HTP	kg 1,4- DCB eq.	62.481	NA	NA
ODP	kg CFC-11 eq.	2.31E-05	3.85E-05	1.44E-05(1.88E-05)
Ph.O	kg C$_2$H$_4$eq.	5.80E-02	2.08E-02	2.24E-02(3.27E-02)
DAR-Elements	kg Sb eq.	1.90E-04	5.01E-01	6.92E-06(1.45E-01)
DAR-Fossils	MJ	2197.00	1517.67	1330(1607)
MAETP	kg 1,4-DCB eq.	58013.10	NA	NA
FAETP	kg 1,4-DCB eq.	2.659	NA	NA

Commented [HA37]: Fabrice can I suggest a slight re-ordering of your results. Your main findings seem to be a large impact on GWP via CO2 emissions or sequestration. This is the motivating factor for using Miscrete, then you also want to evaluate other environmental impacts of this choice.

So I would start the results with description of CO2 emissions and GWP100 for all of your variants of Miscrete, compared to a reference concrete. I think it's important to have this comparison come first.

Then in following sections, look at the other environmental impacts.

This is a nice example paper of an LCA https://www.sciencedirect.com/science/article/pii/S0961953415001166?via%3Dihub which does something similar

Commented [NF38R37]: Thanks, I will discuss the results on GWP100 first and then come back to other impact categories

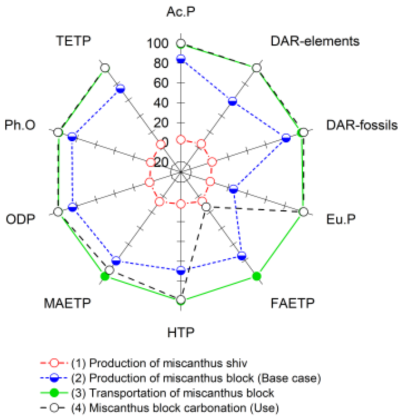

Fig. 7. Cumulative contribution to environmental impacts for major steps in the production of 1m^3 miscanthus blocks 100% represent the maximum value within each impact category through the processes of the production steps (1) to (4).

4.2 Sensitivity analysis for the case

The sensitivity analysis was performed to study the effects of uncertainties and variable data on the robustness of the LCA model. In this study, the sensitivity of the LCA was investigated considering the binder type, binder content and transportation distances. However, different impact categories were quantified in different units and to compare scenarios, an internal normalization was applied with 100% value attributed to the highest value from any scenario within each impact category.

4.2.1 Miscanthus concrete blocks: effect of binder composition and binder content

The sensitivity of the LCA model for miscanthus concrete was investigated at the concrete composition level on two factors: type of binder and binder content. The type of binders that compose blends were hydrated lime, hydraulic lime and pozzolanic materials (Table 1). The variation of binder type and content might incur modifications in the overall mechanical and thermal performance of the composites. These impacts were not considered in this study. Fig. 8 shows the variation of impact categories values as a function of binder content levels in miscanthus concrete. The variations of levels of impact categories scale with binder content levels. However, GWP 100 was the highest impact variation (~52 %) as direct emissions are cut down by the reduction of binder content and biogenic CO_2 capture increased by the increased miscanthus content. The results show that the reduction of b/a from 2.0 to 1.5 allows to reduce water pollution (FAETP) from 2.66 to 1.55 1,4-DCBeq., corresponding to a ~41.7% cut-off. The least affected impact category is Eu.P with ~5.6 % variation for a reduction of b/a from 3.0 to 1.5.

Commented [HA39]: What are you trying to say here?

Commented [NF40R39]: I am trying to explain what is contained in the 'type of binder' scenarios

Fig. 9 presents the variation of environmental impact categories versus the types of binders. All binders are made of 75% hydrated (calcic) lime and varying compositions as shown in Table 1. In general, the incorporation of additions in the binder blends has resulted in the reductions for all impact categories with the highest reductions recorded for 75%CL90s+15%NHL3.5+10% GGBS and 10% PFA (scenarios B and C). The minimum reductions across all impact categories among all the investigated mineral additions correspond to the binder blend containing 10% OPC. The scenarios A and D specifically exhibits the highest values for water pollution impact category (FAETP) corresponding to 2.66 kg 1,4-DCBeq. compared to 0.933 and 1.91 kg 1,4-DCBeq. for scenarios B and C, respectively. This is because the production of cement and lime is highly water-intensive, while the other additions are industrial wastes. The high values related to water and soil pollutions for scenarios A and D can be related to high values of water consumption and pollution associated with lime and cement production, especially containing pollutant such as Cadmium and/or Mercury [55]. However, the variations of impact categories values related to type mineral additions remain low for most of impact categories, allowing potential flexibility in the design of binder blends. The overall effect of binder type and content for miscanthus concrete is shown in Fig 10. In general, the mix parameters that lead to the minimum levels for most impact categories are the reduction of binder content and the use of GGBS. Within the considered range of parameters, the most optimizable impacts are FAETP and TAETP, presenting the highest variations (binder content and type). A linear programming algorithm has been used in section 4.2.2 to find the optimal combination of mix-design parameters using LINGO (Linear Interactive and Discrete Optimizer).

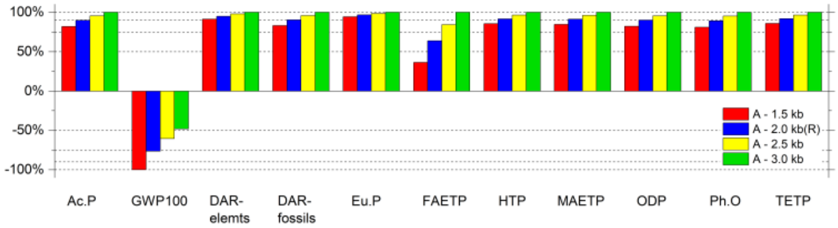

Fig. 8 Effect of binder content on environmental impacts for 1 m3 of miscanthus concrete blocks – binder to aggregate ratio levels (b/a) of 1.5, 2.0 (reference), 2.5 and 3.0.

Commented [HA41]: These aren't the same as what's listed in your table.

Commented [NF42R41]: Yes, these are the results for the scenarii in table 1

Commented [NF43R41]:

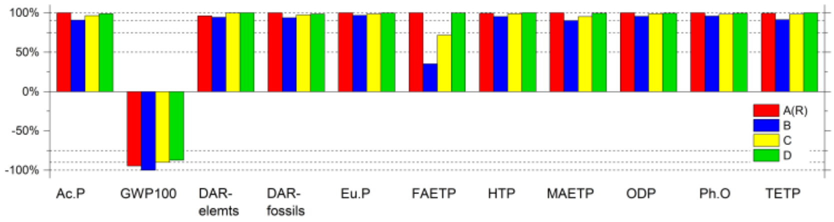

Fig. 9 Effect of type of binder on environmental impacts for 1 m^3 of miscanthus concrete blocks. All binder blends are based on 75wt.% of hydrated lime (CL90s).

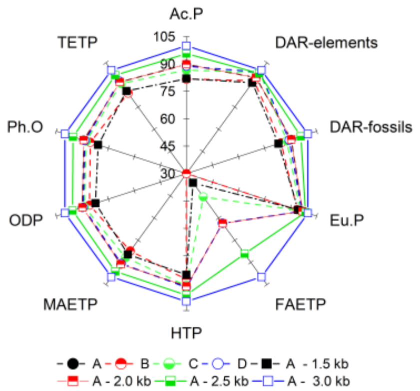

Fig. 10 Effect of binder content and type of binder on environmental impacts for 1 m^3 of miscanthus concrete blocks. Results are normalized on the maximum values within impact categories for all scenarios.

4.2.2 Miscanthus concrete blocks – optimisation of binder content and binder type

The optimum mix design of miscanthus concrete composition may be identified using either qualitative or objective optimisation methods. The results for qualitative analysis suing graphical approach are shown in Fig 10. Based on the normalised data from the actual values of impact categories. Although the results are quite clear for each individual impact category, it remains difficult to assess the overall performance that considers all impact categories. For such multiple objective functions, mathematical modelling remains more reliable than qualitative analysis. Mathematical programming was used to highlight the best mix design among the 8 mix design options using the software package LINGO. Objective functions were composed of selected impact categories out of the CML baseline normalised results by applying weighting factors. While the external normalisation remains the most prevalent in comparative LCAs, there is a substantial risk for the results being driven by the external reference values rather than the actual values from scenarios [56]. In this study, the internal normalisation of impact categories values was preferred and was performed using the equation 5.

Commented [HA44]: By graphical, do you mean just eye-balling which scenarios are best?

Calling this a ‘qualitative’ assessment might be better, if so

$$. \ Q_k^0 = 1 - (maxQ_{ij} - Q_{ij})/maxQ_{ij} \quad \text{(Eq. 5)}$$

Where Q_k^0 is the internally normalized results and Qij is the initial impact category value.

The Q_k^0 values were then weighted with ω_k coefficients and incorporated in the equation 4. Different weighting methods in LCA have been developed and applied to results obtained using different LCIA methods. For instance, Castellani et al. developed a weighting method applicable to ILCD method derived results [57]. Based on the aforementioned study, ILCD compliant weighting sets that aim at various environmental perspectives were proposed in the European guide for interpreting life cycle assessment results [58]. However, weighting remains an optional LCA step for which no CML-compliant weighting method has been proposed [59]. In this study, weighting factors were adapted ILCD-compliant methods and weighting coefficients from similar and/or related impact categories re-adjusted from original values as presented in Table 3. The best mix designs were scenarios B (75%CL90s+15%NHL3.5+10% GGBS) and A-1.5 kb, considering binder composition and binder content, respectively.

Table 3. Optimisation of miscanthus concrete by mathematical linear programming. The values of weights were considered as coefficients ω_k in the equation 4 and applied in LINGO. The constraint is that all impact category values are at least less than average values. The values in bold highlight the strongest weighting factors.

Weighting perspective	AcP	GWP100	DAR-El	DAR Foss	EuP	FAETP	HTP	MAETP	ODP	Ph.O	TETP
Distance to target /Policy target (a)	**9.9**	9.6	8.6	8.0	9.5	8.6	9.4	8.6	8.9	10.3	8.6
Distance to target/ planetary boundaries (b)	4	**28**			10	12		5	4	32	5
Damage oriented (c)	4.6	**42.0**	12.1	12.1			7.6				21.6
Panel based (d)	5.2	**24.2**	7.9	7.9	5.9	11.9	11.5	3.3	4.6	6.4	11.2

(a) Distance to target for EU policies considering binding and nonbinding target at 2020 by Castellani et al. [57]
(b) Considering planetary boundaries (Tuomisto et al. [60]; Bjørn and Hauschild, [61])
(d) Relevance to midpoint indicators based on their contribution to impact at the endpoint (Ponsioen and Goedkoop [62])
(d) Resulting from the combination of different panel-based approaches (Huppes et al. [63])

4.2.3 Miscanthus concrete blocks – Effect of binder transportation distances

Considering regional sourcing of miscanthus shives, transportation of binders is the second contributor to the GWP100 and could eventually influence other environmental parameters. The sensitivity of miscanthus concrete blocks was investigated for eventual transportation distances of 50 km, 100 km and 200 km. Extreme distances (very short distance: 10 km and very long distance: 2000 km) were included in the sensitivity analysis of the LCA model. Fig 11 shows the variation of levels of impact categories versus binder transportation distances. The recorded results were normalised to the maximum impact indicator values among the investigated cases. Different Impact categories were affected unevenly. The lowest effect was observed for eutrophication potential with a variation of ~14% (transportation of distance range of 10 - 2000km) due to the fact that it remains related to the blocks production subsystem that is common to the scenarios. The most affected impact categories recorded are FAETP, DAR-elements, HTP, ODP, and GWP 100 for variations of in the range of 47.4% to 91.5% due to a combination of the extraction and processing of diesel and transportation-related emissions. In general, the higher the transport distance, the higher were the recorded environmental impacts.

Commented [NF45]: What is the main parameter of eutrophication potential of building materials

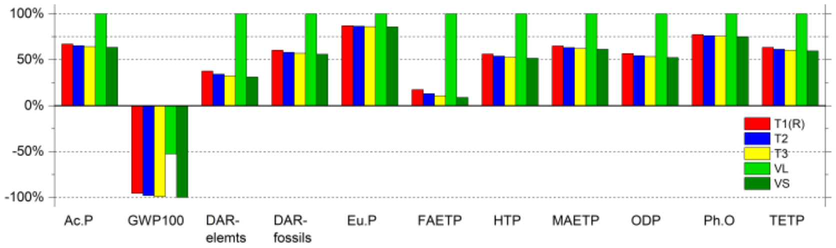

Fig. 11. Effect of transportation distances of binders on environmental impacts for the production of 1 m^3 of miscanthus concrete blocks. Results are normalised to maximum values across the impact categories.

4.3 Environmental performance of miscanthus concrete wall assemblies

Environmental impacts results for the investigated wall structures were normalised to the maximum impact categories among wall structures: base scenario is the timber-framed wall filled with miscanthus concrete (WSA-Ti), miscanthus concrete replacing the insulation in a typical cavity wall (WSA-Br.) and standard solid wall insulated with mineral wool (WSS-Min.w). Table 4 summaries recorded values for all impact categories calculated for the functional unit (f.u) of 1 m^2 WSA-Ti. The energy and materials flows associated with the construction activities is negligible compared to the energy inputs for materials production and supply. Hence, no further breakdown of processes beyond materials production and supply was performed. The impact category levels for the wall assemblies , as reported in Appendix B, show that the most noticeable impact categories are GWP100 (- 130 $kgCO_2eq$./f.u), and the depletion of abiotic resources (~1063 MJ/f.u) which is mainly attributable to the production of diesel and gas used for the extraction, transportation, and processing of binders.

Fig. 12 compares the environmental impacts categories for the investigated wall assembly scenarios. All assessed impact categories levels remain the lowest for WSA-Ti wall scenario except for Eu.P, ODP, Ph.O and TETP. Compared to a typical standard wall assembly (WSS-Min. w), the levels of these impacts remain high for miscanthus concrete-based wall scenarios (WSA-Br. and WSA-Ti) and are suspected to originate from the agricultural subsystem processes. In all, the WSA-Br. exhibits the highest levels for most impact categories. This can be attributed to the high energy requirement (~700 kWh/tonne) for the firing of clayey materials at temperatures between 900 and 1150 ºC [64]. However, GHG emissions of the WSA-Br. scenario were offset by the CO_2 absorption of miscanthus-lime blocks to a low net value of ~6.89 kg CO_2eq/m^2. The highest variation across wall assembly scenarios was recorded for GHG emissions with a 187% variation between WSA-Ti and WSA -Min.w while the lowest variation was obtained for DAR-fossils with 0.7%. In general, comparing WSA-Br. and WSA-Ti reveals that the association of clay bricks outer leaf layer with miscanthus concrete in a wall structure offsets most of benefits from miscanthus concrete and leads to values of impact indicators even higher than those of WSA-Min. w for most impact categories. However, the GWP100 for the WSA-Br. scenario remains ~80% lower than that of WSA-Min.

w. Although associating bricks to miscanthus blocks result in net positive GHG emissions in newbuilt scenarios, the application remains plausible in retrofitting situations. In a similar study, in a retrofitting scenario of a Victorian houses' uninsulated brick walls using hemp concrete, Griffiths and Goodhew reported an average CO_2 storage of 316 tCO_2eq [65].

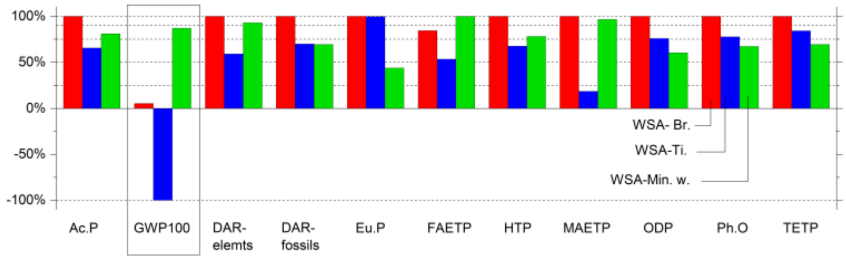

Fig. 12 Environmental impacts of blocks of miscanthus-lime wall assemblies and standard solid mineral wool insulated wall.

4.4 Hot spots on GHG emissions

The results discussed in sections 4.1 through 4.3 show that emissions of GHG is by far the most affected impact category. In this section, LCA results are discussed for the production of 1 m^3 of miscanthus blocks and miscanthus wall assemblies to highlight elements of potential improvement. The results presented in Fig. 7 summarise the key steps involved in the production of miscanthus concrete blocks and their respective cumulative environmental impacts. It is shown that the production of miscanthus blocks remain by far the most critical step for most impact categories contributing for at least ~ 60% to all impact categories except for eutrophication potential. The overall net GHG emissions associate to the production of miscanthus concrete blocks were found to be ~ -216 $kgCO_2eq/m^3$. The production of miscanthus blocks remains the process that contributes the most to GHG emissions of which ~ 92.2% are attributable to the production of binders (226.42 $kgCO_2eq/m^3$). The absorption of CO_2 can achieve values ~ -518.9 kg CO_2eq/m^3 of which 53.2% and 31.2 % are attributable to miscanthus biogenic absorption and lime binder carbonation, respectively. The sensitivity analysis has revealed that the reduction of binder to aggregate ratio leads to 23.5% and 51.8% decrease of GHG emissions, respectively for 2.0 to 1.5 and 3.0 to 1.5 binder to aggregate ratio reductions. On the other hand, the incorporation 10wt% mineral additions (GGBS, OPC, PFA) reduces the GHG for less than 7.1 %.

Wall assemblies incorporating miscanthus concrete (timber-framed and brick-cladded) performed better than the typical mineral-wool insulated solid wall. Timber-framed wall benefits from both low energy processing of wood and its supplementary biogenic CO_2 absorption. Timber-framed wall recorded carbon dioxide storage ~ -130 CO_2eq/m^2 and the brick cladded wall exhibited net GHG emissions ~6.89 CO_2eq/m^2, of which ~22.5% and 49.2% of positive emissions were attributed to the production of clay bricks and lime binder, respectively, for a total of 138.3 CO_2eq/m^2. The overall negative emissions recorded were -131.43 CO_2eq/m^2 of which ~ 63% and 36.9% were attributed to miscanthus biogenic CO_2 absorption and binder carbonation, respectively. The overal GHG emissions recorded for the standard mineral wool insulated wall scenario were ~113 kg CO_2eq/m^2.

A comparative analysis of the obtained results with existing studies is difficult due to fundamental differences among models in terms of wall structure, functional unit definition and objectives of studies. Nevertheless, the actual results for timber-framed miscanthus wall can be compared to the UK study on hemp concrete walls carried out by Ip and Miller [17] and to the French studies of Boutin et al. [18] and Pretot et al. [66]. Ip and Miller reported a net GHG emissions of -36.08 kg CO_2eq/m^2 for a 300 mm non-rendered, non-cladded wall while this study reports a net GHG emissions of ~ -130 kg CO_2eq/m^2. The French study of Boutin et al. [18] reported GHG emissions values of -35.53 kg CO_2eq/m^2. The fundamental differences in these studies lie in the low energy farming of miscanthus, its local availability that cuts down transportation-related impacts and high aggregate content of the investigated mixes that maximise biogenic CO_2 capture.

5. Conclusion

Bio-based building materials present viable potential as insulating materials. The recent growing awareness of sustainability in buildings sector, in large part due to the actual environmental concerns, has revitalized research interests on these materials. Even though, hemp-lime has emerged and remains widely used for buildings envelopes, miscanthus concrete has not be studied to any meaningful level compared to that of hemp. In this study, an attempt is made to assess potential environmental impacts of incorporating miscanthus shives in lightweight blocks and the impact of miscanthus blocks on the overall life cycle of wall assemblies in which they are integrated.

The reported results show that GHG emissions are the most affected environmental impact category as expected. In fact, miscanthus blocks sequestrate GHG emissions that off-set the binder production emissions to enable a storage of - 216 kg CO_2eq/m^3. The environmental implications of the system to a regional level could be significant. The association of miscanthus blocks with bricks cladding however lead to low emissions ~ 6.89 kg CO_2eq/m^2 while timber framing enhances the wall carbon storage levels ~ -130 kg CO_2eq/m^2. The former could be potentially beneficial in retrofitting the existing brick walls.

The analysis of contribution of various factors show that binder content levels are the most influential factors for most of the environmental impact categories and for GWP100 in particular. Interestingly, the binder composition has a relatively little effect on GHG emissions. This infers even more flexibility in designing blends of mineral additions in the 10% range to improve the performance of the composites without significantly impacting their environmental performance. Although most of the overall GHG emissions are sequestered and stored with the incorporation of miscanthus in wall assemblies, the environmental impacts associated mainly with farming of the crop are to be considered and carefully accounted for. For instance, the use of miscanthus in timber framed wall (WSA-Ti) increased the eutrophication potential by 55.7% compared to standard mineral wool insulated wall. However, the later could be significantly reduced through the adoption of environmentally friendly agricultural practices. The lack of specific site data and the use of generic data from databases impede on the accuracy of results analysis. The use site specific data for local and regionally sourced materials can overcome these limitations and allow the application of the results to the whole building life cycle assessment. Future work will focus on whole building model including operational energy and cost analysis. This will allow a scaling-up at national level considering the type and age of actual housing stock and identifying buildings that need retrofitting to conform to actual thermal performance requirements; taking into account the potential carbon storage.

Commented [HA46]: Wasn't the increase the same for the WSA-Br wall? (Both blue and red bars are higher than green bar in Figure 12)

Acknowledgement and funding:

This article is part of the ongoing research at the University of Exeter, College of Engineering Mathematics and Physical Sciences. This research project is supported by a NERC GW4+ Doctoral Training Partnership studentship from the Natural Environment Research Council (NERC) and the National Productivity Investment Fund (NPIF) [NE/R011621/1] and is thankful for the support and additional funding from CASE partners, Miscanthus Nursery Limited and Agrikinetics Limited. ABH acknowledges funding from EPSRC Fellowship EP/N030141/1 and NERC project NE/P019951/1.

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Supplementary data

Appendix A: Diesel consumption associated with agricultural subsystem of miscanthus production

Agricultural activities	Power and performance	Diesel (L/ha)
Ploughing	150 hp plough and 1 ha/h	13.0
Weed control (Glyphosate 3kg/ha)	80 hp tractor+ sprayer 1.2 ha/h	3.5
Rhizome planting	46 hp tractor + planter and 1.5 ha/h	9.9
Harrowing	250 hp power harrow and 1.3 ha/h	17.5
Harvesting	500 hp forage harvester and 2ha/h	17.0
Baling	300 hp baler and 2 ha/h	15
Transport of bales (field to storage)	150 hp tractor+ trailer + handler and 5ha/h	12.5
Total		88.4

Appendix B: Impact categories levels for base scenario: the timber-framed wall filled with miscanthus concrete (WSA-Ti), miscanthus concrete replacing the insulation in a typical cavity wall (WSA-Br. scenario) and standard solid wall insulated with mineral wool (WSS-Min.w scenario).

Impact category	Abbreviations	Units	WSA-Br	WSA-Ti	WSS-Min_w
Acidification potential	Ac.P	kg 1,4-DCB eq.	4.89E-01	3.21E-01	3.97E-01
Climate change	GWP 100	kg PO4--- eq.	6.89E+00	-1.30E+02	1.13E+02
Depletion of abiotic resources - elements, ultimate reserves	DAR-Elements	kg CO2 eq.	1.95E-04	1.15E-04	1.81E-04
Depletion of abiotic resources - fossil fuels	DAR-Fossils	kg SO2 eq.	1.52E+03	1.063E+03	1.05E+03
Eutrophication potential	Eu.P	kg 1,4- DCB eq.	2.09E-01	2.08E-01	9.18E-02
Freshwater aquatic ecotoxicity	FAETP	kg CFC-11 eq.	1.04E+01	6.55E+00	1.23E+01
Human toxicity	HTP	kg C2H4eq.	4.69E+01	3.17E+01	3.67E+01
Marine aquatic ecotoxicity	MAETP	kg Sb eq.	1.49E+05	2.75E+04	1.44E+05
Ozone layer depletion	ODP	MJ	1.38E-05	1.05E-05	8.33E-06
Photochemical oxidation	Ph.O	kg 1,4-DCB eq.	3.58E-02	2.78E-02	2.41E-02
Terrestrial ecotoxicity	TETP	kg 1,4-DCB eq.	4.02E-01	3.38E-01	2.79E-01