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Highlights

- Size of fragments important for blocks mechanical properties
- Low leaf/stem ratio is an important factor for improving mechanical properties
- Load-bearing miscanthus block worse for environment than conventional alternatives
- Climate change impact is not the only focus for developing biobased concretes
- Indirect consequences of Land Use Change important for environmental performances

Abstract

Concrete blocks prepared with Portland cement and miscanthus-based aggregates were prepared in order to check if the miscanthus genotype may influence their mechanical properties and to perform an environmental assessment. To produce lightweight, load-bearing concrete blocks using miscanthus stem fragments as aggregates in a single mixing method turned out to be impossible, although trying to optimize the concrete formulation. The results show that genotypes and size of miscanthus fragments controlled the mechanical properties of the final blocks. The lower was the amount of light elements such as leaves and sheath, the better were the mechanical properties of the blocks. When comparing genotypes with the same leaf/stem ratio, it was not possible to see a correlation between the biochemical composition of the stem and the compressive strength of the blocks. A probable explanation is the small variation of biochemical composition between genotypes. Using life cycle analysis tools, miscanthus block were not found to be competitive with conventional alternatives (concrete block and lightweight pumice block) when trying to increase compressive strength above 3 MPa. However, compared to non-load bearing alternatives (light clay brick), blocks integrating miscanthus had a better global environmental performance mainly due to a favorable climate change impact. The present work also points out the risk of decreasing the environmental performances when cultivating the crop on land in competition with food, because of the impacts of indirect consequences of Land Use Change.

Keywords

Miscanthus; Concrete; Life cycle assessment; Mechanical properties; Genotype

1- Introduction

The need for low environmental impact has led to a growing demand for novel concretes, with lightweight concretes (800-2000 kg/m^3) being a possible option. They can be prepared in different manners [Li et al. 2019; Zeng et al. 2018; Dixit et al. 2019]. One of them consists in substituting part of the mineral aggregates with biomass materials, mostly extracted from plants. Compared to traditional materials, such plant-based construction materials can have several advantages such as the reduction of weight and of carbon emission, favorable hygrothermal and acoustical properties and better life cycle assessment and effects on health [Chabanes et al. 2018; Saez-Perez et al. 2020; Liu et al. 2017; Barbieri et al. 2020]. Many scientific articles have been published, describing the use of a large variety of plant materials such as hemp, coconut, jute, flax, sisal and many others, see for ex [Amziane & Sonebi 2016; Saez-Perez et al. 2020; Onuaguluchi & Banthia 2016; Jami et al. 2019; Alengaram et al. 2013]. Biomass fiber-reinforced concretes are interesting because they have the potential of solving the expected progressive shortage of mineral resources (including sands and gravels) [Yang et al. 2019]. However, the use of biomass-reinforced concrete is limited due to the natural variations in the quality of biomass which may lead to some unpredictability of the properties of the final products [Alengaram et al. 2013; Karade et al. 2006; Merta & Tschegg 2013] and to chemical, physical and dimensional changes which can occur within the natural fibers with time, hindering the dimensional stability and mechanical properties of concretes [Tonoli et al. 2013; Bederina et al. 2012]. The main reason for the lack of mechanical performance derives from biomass fibers being softer and lacking the stiffness of the mineral aggregates they are replacing. As a result, the compressive strength of biomass-reinforced concrete is poorer than that of conventional concrete [Amziane & Sonebi 2016; Turgut 2007; Prusty et al. 2016; Çomak et al. 2018]. Among the many possibilities for choosing the plant from which organs or group of organs will be used, miscanthus is a potentially good candidate. It is a perennial C4 grass requiring low nitrogen inputs (Zapater et al. 2017), having a high aboveground biomass production [Zub et al. 2011] and good mechanical properties of its stem fragments [Kaak and Schwarz, 2001; Kaack et al. 2003], which can be used for preparing polymer composites [Girones et al. 2016; Chupin et al. 2020]. The use of miscanthus was first explored by Pude et al (2002; 2003; 2004; 2005) for the preparation of plant-based concrete. They studied different genotypes to select for concrete composite preparation those with low silicon content, in combination with large cellulose and lignin contents to strengthen the stem fragments (called fibers afterwards). Other characteristics such as the amount of leave and the role of water from the initial fibers to the final concrete were considered. Their conclusions are that upon contact with water and cement, most of the water is absorbed by cellulose which is swelling in the sclerenchyma ring with water and cement rapidly migrating to the outer ring. Everything considered, including the fact that the permanent binding of water in the concrete is of great importance, they found that the best genotype maximizing all the needed parameters is *M. x giganteus*. Then, the preparation and properties of miscanthus-based concretes were further explored. Acikel (2011) added low amounts of miscanthus fibers in a sand, gravel, cement mixture and found that this was bringing an increase of the compressive strength of blocks of 4-10%. Merta and Tschegg (2013) compared the fracture energy of concrete reinforced with chopped fibres of hemp, wheat straw, and miscanthus. The latter increased the fracture energy of concrete by only 5%, far below the increase of 70% observed with hemp, this being due to the low surface roughness, which limits stress transfer. Waldmann et al. (2016) prepared miscanthus-based concrete blocks where the miscanthus fibers were mineralized with various chemical substances like magnesite, calcium hydroxide, chalk and calcium chloride, the latter turning out to bring the best results in term of resistance to compression. Their mixtures had compressive strength in the same order as concretes prepared using other-than-vegetal aggregate lightweight concrete, from 5 to 7 MPa when increasing the specific weight from 1000 to 1250 kg m^{-3}. Courard and Parmentier (2017) looked at the carbonation effects of cement in the presence of miscanthus and to the effect of a pre-mineralization of the miscanthus fibers. They found that capturing CO_2 in concrete is an environmentally favorable process which allows to increase the abrasion resistance and the mechanical performances of concrete blocks. Chen et al. (2017; 2020) measured the acoustic performances of miscanthus concrete. They found that ultra-light concretes (specific mass of about 550 kg m^{-3}) with 30% v/v miscanthus fibers have a thermal conductivity of 0.09 W m^{-1} K^{-1} and a high acoustic absorption coefficient (0.9) at low frequencies. The dosage and shape of miscanthus fibers have a significant effect on these properties. Ntimugara et al. (2020) looked at the possibilities for using miscanthus coming from Southwest England to develop building materials. Pereira Dias and Waldmann (2020) prepared miscanthus-based concrete varying water/cement ratio as well as the amount of miscanthus fibers, being pre-treated with a silica sealant or with a mixture of quartz and calcium hydroxide. The objective was to prepare loads-bearing blocks. A silica treatment, associated or not with an alkali extraction, was found to increase the compression strength [Boix et al 2016]. The main result of Pereira Dias and Waldmann (2020) study is that a silica sealant applied on the miscanthus fibers can be beneficial. Compressive strength in the order of 12-14 MPa was obtained for specific mass of over 1500 kg m^{-3}. As observed for all biomass-based concrete, increasing density of the mixture increases the compressive strength. Compressive strength of 5-8 MPa were obtained with specific masses around 1000 kg m^{-3}.

One of main issues for combining plant biomass with cement is the release of chemicals (mainly polysaccharides, sugar oligomers, sugars, lignin), extracted from the biofibers and reacting unfavorably with cement particles. When miscanthus fibers are placed in a cement-water-sand mixture, there is a large decrease of the cellulose and xylose content in the fibers, these two molecules being adsorbed on cement particles [Boix et al. 2020]. These results stress the importance of choosing the genotype and controlling the whole preparation process.

In all miscanthus-based concrete work, it is taken as granted that the use of miscanthus to prepare concrete is environmentally favorable but, despite many life cycle assessment (LCA) studies were performed on different uses (ethanol production, electricity, board, pellet, biochar, heat etc.) of miscanthus [Krzyżaniak et al. 2020, Lask at al. 2018, Fusi et al. 2020, Yesufu et al.2019, Tadele et al. 2019, Peric et al. 2018], no study having been performed on concrete reinforced miscanthus. However, looking to the various LCA studies on mainly hemp concrete, the environmental performances of bio-based concrete show a contrasted picture. A good performance on the climate change impact has always been demonstrated, although to a certain extend (-1.6 kg CO_2eq m^{-2} to -36.08 CO_2eq m^{-2}) according to Arrigoni et al. (2017). However, the added value on the other impact categories is not always verified. Heidari et al. (2019) calculated around 20% better performances on human health and energy consumption but 300% worse performance on ecosystem quality compared to a reference wall. Prétot et al. (2014) highlights that hemp concrete may also generate a more significant impact on resources consumption, water consumption and water pollution in comparison to a brick wall and concrete blocks.

The purpose of this paper is to study the preparation, mechanical properties and life cycle assessment (LCA) performances of miscanthus-based concrete, prepared without pre-treatments of the biomass. Pre-treatments [Lo & Navard 2016] such as removal of extractives by alkali treatments or silanization can be too costly to be industrially implemented. Regarding LCA, the standardized methodology (ISO 14040/44) was used to evaluate the potential environmental impacts of a product, a process or a service. The objective was to compare the environmental performances of miscanthus reinforced blocks to conventional alternatives and identify how to improve them in a perspective of ecodesign. It is hypothesized that the genotype may influence the mechanical properties and that the use of cement to reach load-bearing characteristics may be an obstacle to reach good environmental performances.

2-Materials and methods

2.1 Raw materials

Portland cements (52.5R CE CP2 NF by Calcia, Guerville, France) were stored in sealed containers to avoid moisture adsorption. Sands with two granular sizes of 0-2 and 0-4 mm were purchased from Castorama (Sophia Antipolis, France).

The vegetal aggregates used in this study are made of miscanthus stem fragments, broken, and cut at various lengths (1, 2 or 3 cm, with variable diameters of the fragments) by Fibres Recherche Dévelopment FRD (Troyes, France). In order to study the influence of light parts of the stems (leave and sheath), leaves were removed on 1 cm fragments from H5 genotype. Air was flown horizontally to a stream of miscanthus fibers falling from a controlled height. Heavy fragments will not change their trajectory and continue their linear fall, whereas lighter fragments will be pushed away. Thus, the fragments can be separated by controlling the speed of the air blown, the distance from the floor at which the air is blown, and the distance between the collection point and the floor. Stems, either with or without leave, were used. Fragments are thus mixtures of tissues and their composition varies since the biochemical characteristics are depending on the location of internodes. To be in line with literature on this topic, these stem fragments will be called fibers in all this article.

Two types of experiments were conducted. A first set of experiments was dedicated to study the preparation of miscanthus-based concrete blocks and to the life cycle assessments. This was performed with a *Miscanthus × giganteus* genotype planted in Ecurie des Prés Hauts

(France) and harvested in September 2014. This sample will be called "Granulo Mg" in the following. The size distribution of Granulo Mg fragments is shown in Figure 1S.

A second set of experiments was used to explore the genotype effect. Six contrasted genotypes were chosen to offer wide phenotypic variability and their origin is given in Table 1S. Two of the genotypes were *M. x giganteus* interspecific hybrids: a biomass genotype (coded GiGB) and the Floridulus (Flo) ornamental variety. Two other genotypes were varieties from the *M. sinensis* species: a biomass tetraploid Goliath variety (Gol) and a diploid ornamental Malepartus variety (Mal). The two remaining ones belonged to the *M. sacharriflorus* species: a biomass tetraploid (H5) and an ornamental diploid (Sac). The corresponding trial was a complete block design with three blocks and was planted by hand in spring 2007 at INRAE Estrées-Mons (Péronne, France) at a rhizome planting density of 2 plants per m^2. Each harvested plot consisted of 16 m^2 which contained four rows of eight plants and each plot was surrounded by a border row. The trial received no nitrogen input and weeds were regularly removed manually. No fertilizer and pesticides were applied. The harvest was carried out on a mature 8-year-old crop in February 2015 when the dry matter content reached 65% on average.

Granulo MG harvested in September 2014 was used for part 3.1 (Influence of preparation and process parameters) and 3.3 (Life cycle Assessment). The six genotypes harvested in Spring 2014 were used for Part 3.2 Effect of miscanthus genotypes and sizes).

2.2 Concrete preparation, curing and testing

2.2.1 Preparation of the concrete mixtures and curing

Water contents of sand and miscanthus fragments were measured by using a halogen moisture analyzer Mettler Toledo HX204 (Mettler Toledo, France) before each batch preparation. Drying temperature was set at 105 °C, and switch-off criterion to stop drying was less than 1 mg mass loss for a 50 second period. Approximately 30 kg of fresh concrete were prepared for each batch. Water was collected from the public drinking supply network. The amount of water added during mixing was adjusted depending on the amount of miscanthus fibers present in the mix. The water-to-cement ratio ranged between 0.59 and 1.52. The total quantity of water in each mixture was measured as the amount of water added and the water contained as humidity in sand and miscanthus fibers. Concrete blocks were prepared in a laboratory conditioned at 20 °C. The proportion of cement / miscanthus / sand was varied.

The preparation of the concrete blocks was performed in one step, lasting about 20 min. Mixing was carried out in a Kniele KKM-L 30 mixer (Kniele, Germany). The order of component introduction was:

First, miscanthus and the pre-wetting water (40 wt% of miscanthus mass) were mixed. Once the mix was homogenous, sand was added, followed by the incorporation of cement. Finally, the rest of the needed water was added to the mixer gradually. Mixing time, calculated from the moment the mixing water was added, lasted for 8 minutes. Then, the fresh concrete mix was unloaded and concrete blocks were immediately prepared. The needed amount of the fresh mix was poured into a 15×15×15 cm^3 metallic mold, attached to a vibration table (Netter Vibration NV, Germany). Demolding oil (Deltapro, France) was sprayed into the mold before fresh concrete was poured in. Concrete blocks were formed under the vibration-compaction method. Samples were vibrated with a frequency of 50 Hz while being simultaneously compacted with a hammer. Time for vibration-compaction varied from 20 sec to 90 sec, depending on the characteristics of the concrete mix. After demolding, the concrete blocks were stored in a temperature-controlled room at 20°C and covered with a plastic sheet for 7 days.

Various mixtures were tested to investigate the effect of miscanthus/cement/sand contents on the compression strength of the obtained concretes (Table 1). Based on dry mass, miscanthus Granulo MG content in the concrete was varied from 5 wt% to 12 wt%, whereas cement content was varied from 20 wt% to 40 wt%, the rest of the mixture being sand and water.

Table 1: Composition of concrete mixes (final total mass 1000 kg).

Cement (kg)	Miscanthus (kg)	Sand (kg)	Water-to-binder ratio
400	120	480	0.71
	96	504	0.66
	72	528	0.59
300	120	580	0.94
	91	609	0.84
	62	638	0.70
200	120	680	1.52
	86	714	1.22
	52	748	1.04

2.2.2 Testing

At the end of the curing period, the specimens were weighted, and their dimensions were measured with a Vernier caliper (precision 0.1 mm). Dimensions were used to calculate the volume. The compressive tests were conducted on a hydraulic DARTEC HA 250 instrument (Zwick, Germany) at constant deformation speed of 5 mm/s, measuring force and displacement, used to calculate stress and deformation.

The volume change of a concrete block in percentage (%) was calculated according to the equation:

$$Volume\ change\ (\%) = \frac{V_7 - V_0}{V_0} \times 100\%$$

where V_7 and V_0 are the volume of the concrete block at 7 and 0 days, respectively. To check the effect of block orientation upon the mechanical properties, a set of 5 cubes were prepared with Granulo MG miscanthus fibers in the same conditions and their mechanical properties were measured by applying load on two different orientations, being axial compression at 0° and perpendicular compression at 90° towards the compaction direction (Figure 2S).

2.2.3 Reference composition

A reference composition will be used for all comparisons between different preparation procedures. The reference composition was arbitrary set as 40 wt% cement, 48 wt% sand and 12 wt% miscanthus (based on dry mass) with a total water-to-binder ratio of 0.64.

2.3 Biomass composition

The dry miscanthus samples were ground and sieved at 0.1 mm before exhaustive water, then ethanol extraction in a Soxhlet apparatus. The recovered extractive-free samples, corresponding to cell wall (CW) samples, were dried at 50 °C before their compositional analyses. The lignin content (ABL) was measured using the acetyl bromide lignin method according to Sibout et al. (2016). Lignin composition was determined from the relative percentage of the *p*-hydroxyphenyl (H), guaiacyl (G), and syringyl (S) monomers released by thioacidolysis of CW samples, as described in (Méchin et al. 2014).

The hemicellulose and cellulose levels as well as the hemicellulosic neutral sugars were measured as described in (Chupin et al., 2017) and from 10 mg of the aforementioned dried

CW samples. The CW samples were kept in 2.5 M trifluoroacetic acid (TFA) for 1.5 h at 100 °C. To determine the cellulose content, the residual pellet obtained after the TFA hydrolysis was rinsed twice with ten volumes of water and hydrolyzed with H_2SO_4. The monosaccharides released by TFA and H_2SO_4 hydrolysis were diluted a minimum of 500 times and quantified using an HPAEC-PAD chromatograph. 20 mg DW of ground samples were then extracted in 1 mL 80% ethanol for 30 min at 78 °C, then centrifuged (1000 rpm). The supernatant containing sugars was placed in 50 mL graduated flask. The pellet was suspended in 1 mL of 80% ethanol in same condition as previously, this procedure being carried out 3 times. After homogenization and aliquot filtration through membrane filter 0.22 µm, the mono and di saccharide contents were quantified using an HPAEC-PAD chromatograph. The separation was carried out by Car-boPack PA1 Column at 30 °C with an isocratic elution of 150 mM sodium hydroxide. The hemicellulosic neutral sugars characterized were the following: arabinose (Ara), galactose (Gal), glucose (Glc), rhamnose (Rha), and xylose (Xyl). The glucose (Glc) from cellulose was also measured. The main phenolic acids, ester-linked *p*-coumaric acid (CA) and ferulic acid (FA) were measured by mild alkaline hydrolysis, followed by solid phase extraction and then HPLC analyses according to (Ho-Yue-Kuang et al., 2016). For HPLC separation, 1 µl of sample was injected onto an RP18 column (4×50mm, 2.7 µm particle size, Nucleoshell, Macherey-Nagel) with a flow rate of 0.5 ml/min. The eluents were 0.1% formic acid in water (A) and 0.1% formic acid in acetonitrile (B), and the gradient was as follows: 0–3 min, 0% B; 12 min, 20% B; 14 min, 80% B; 16 min, 0% B. The quantitative determination of alkali-released CA and FA was performed from the 250–400 nm DAD chromatograms and after calibration with authentic compounds.

The composition and leaf/stem ratio of the six genotypes are given in Table 2S. To approach at best the mean composition of the whole stem while composition measurements are performed on small amounts of samples, the composition used in the following of the paper was the mean value of the composition of the top and the bottom internodes of each genotype.

2.4 Statistics

The experimental design allowed to compare six genotypes for strength measured at 7 and 28 days as well as volume change. The corresponding ANOVA included the genotype effect and the technical repetition effect. The three sizes of fragments, measured on the GIGB clone of Miscanthus x giganteus, were also compared for the same variables. Accordingly, the ANOVA included the size effect and the technical repetition effect. The comparison of genotype means as well as size means was based on the Student–Newman–Keuls test. All ANOVAs were based on the aov function of agricolae package and the SNK comparisons on the SNK.test function. For all statistical tests, the probability level was considered at 0.05.

2.5 Life Cycle Assessment

2.5.1 Notation used in the life cycle assessment studies

Acidif. (Acidification); Clim. Chang. Excl. (Climate change excluding biogenic carbon); Ecotox. Freshwat. (Ecotoxicity freshwater); Eutr. Freshwat. (Eutrophication freshwater); Eutr. Marine (Eutrophication marine); Eutr. Terres. (Eutrophication terrestrial); Hum. tox. Cancer (Human toxicity cancer); Hum. tox. non-cancer (Human toxicity non-cancer); Ion. rad. (Ioniozing radiation); Land Use (Land use); Oz. Depl. Ozone depletion); Part. Mat. Form. (Particulate matter formation); Photoch. ozone form. (Photochemical ozone formation); Water dep. (Water depletion); Min., foss. & renew. Depl. (Mineral, fossil and renewable depletion).

The notations for the potential environmental impacts used in this study are reported in Figures 6, 7, 8 and 10.

2.5.2 Functional unit and reference flows

The assessment was conducted for two different functions with the Granulo MG samples: (1) non-load-bearing block with 4 MPa compression resistance and (2) load-bearing blocks with 6 MPa compression resistance, both with a specific mass at about 1000 kg m^{-3}. These two compression resistance values are based on norm NF EN 206-1. The minimum compression resistance limit for load-bearing light blocks is 9 MPa for cubic test samples. It was impossible to reach such value keeping the specific mass below 1000 kg m^{-3}. So, the highest attained resistance, 6MPa, was kept as the load-bearing limit to carry on the LCA analysis. It must be noticed that cofunctions such as heat and acoustic insulation were not considered. This is a limitation to the comparison between miscanthus and alternatives blocks. The functional unit is 1 m^2 of wall keeping its function over 100 years. The reference flows for each scenario are reported in Table 2.

Table 2: Function, functional units and reference flow for each scenario.

Function	Scenario	Functional unit and reference flow*
Non load-bearing scenario blocks	Miscanthus 8% DM	1 m^2: 52 kg (44 blocks 40 mm thickness)
	clay bricks	1 m^2: 34 kg (10 blocks 40 mm thickness)
Load-bearing scenario blocks	Miscanthus 5% DM	1 m^2: 221 kg (44 blocks 150 mm thickness)
	100% concrete	1 m^2: 178 kg (8 blocks 200 mm thickness)

* Miscanthus blocks have 150/150 mm length and width, clay bricks 500/200 mm length and width, full concrete blocks 500/250 mm length and width. DM stands for dry matter.

It is not expected that the production of miscanthus reinforced concrete blocks will have large-scale consequences on any markets. Thus, the LCA was performed according to methodology recommended by the European Union in the frame of the International Life Cycle Database (ILCD) [European Commission 2010] for a “Micro-level decision support” LCA’s type. This implies that background processes can be determined in an attributional way as well as that the co-function that cannot be solved by a subdivision of the system shall be solved in priority by the system expansion approach.

2.5.3 System boundaries and sub-scenarios

This is a cradle-to-grave LCA. It considers the main processes, resources consumption and waste from the production of blocks to the disposal of the wall in France as reported in Figure 1. The air drying is not considered because it does not require energy and resources. However, the infrastructure required for the drying is considered for the blocks production. The transportation phases are identified with the “T” letter. During the wall life, no maintenance is required. This step is nevertheless reported because of the carbonation process. The carbon uptake from atmosphere by the carbonation of the calcium oxide in concrete is calculated from [Pommer & Pade 2005]. To allow taking into account the delayed carbon storage over the 100 year’s timeframe of climate change impact evaluation method and life of the wall, the benefit of the carbon uptake from atmosphere is reduced by 50.5% according to the methodology recommended by the European Commission [European Commission 2010]. The carbon storage in miscanthus is also evaluated. 45% carbon in miscanthus dry mass was considered. The co-functions were solved according to the system expansion approach. The co-functions arise at the end-of-life when a fraction of the wall is sorted and recycled as ballast. The assessment was performed in priority according to French conditions (e.g., electricity mix, agricultural machinery, etc.) then European (e.g., Portland cement production) or Switzerland (e.g., mortar production) and global (e.g., unspecified transport lorry) if no French datasets were available.

<u>Figure 1</u>: LCA system boundaries.

Sub scenarios have been considered for the miscanthus production. Two different yields of dry matter (DM) and agricultural practices have been modelized. A highly productive land with a 14.8 t ha^{-1} $year^{-1}$ DM (HighProdLand or HPL) and a lower productive land with 6.4 t ha^{-1} $year^{-1}$ DM (LowProdLand or LPL) that requires fertilization. In the baseline scenario, neither direct no indirect consequences of Land Use Change (dLUC/iLUC) are considered, miscanthus being cultivated more than 20 years on the same field not in competition with food production. It is assumed this scenario is the best representation of the performance of the miscanthus on a mid-term perspective, once the sector will develop at an industrial scale and where the dLUC and iLUC are no more relevant. Two additional scenarios were modelled. They represent the performances for the first 20 years of the miscanthus cultivation, before an equilibrium of the direct and indirect variation of the Soil Organic Carbon (SOC) stock is reached. The first scenario, called dLUC, considers that miscanthus is not in competition with food production and that it takes place on a land with a high SOC. In this case the cultivation leads to a SOC variation between -0.5 to 0 tC ha^{-1} $year^{-1}$ over 20 years [Ferchaud unpublished] thus to CO_2 emissions. An average value of -0.25 tC ha^{-1} $year^{-1}$ was used. The second scenario, called d+iLUC, is representative of a miscanthus cultivation on a land in competition with food production. In this case the miscanthus is cultivated on a land with a low SOC stock and it leads to a direct SOC variation between +0.2 to +0.6 tC ha^{-1} $year^{-1}$ over 20 years [Ferchaud unpublished], implying a CO_2 storage. An average value of 0.4 tC ha^{-1} $year^{-1}$ was used. However, the indirect CO_2 emission due to indirect consequences of land use change are also taken into account. According to [Audsley et al., 2009; Schmidt et al., 2011; Flysjö et al. 2012] the indirect CO_2 emissions range from 1.43 to 8.58 t CO_2 ha^{-1} $year^{-1}$. An average value of 5.00 t CO_2 ha^{-1} $year^{-1}$ was used (1.36 t ha^{-1} $year^{-1}$ C). Moreover, as a rough estimation and to maximize impacts, it has also been assumed that the use of 1 ha to produce miscanthus in France instead of a food crop will be equivalent to the transformation and the occupation of 1 ha of tropical forest.

2.5.4 Life cycle inventory, limitations and result calculations

The assessment was performed on the LCA software GaBi®. Table 3S reports the origin of the foreground and background data to calculate the life cycle inventories (LCI). The transport related to the supply of raw materials at each step as well as to the end-of-life is considered thanks to the average transport as defined in the Ecoinvent 3.3 database. The potential environmental impacts were calculated with the version 1.09 of the environmental impact evaluation set recommended by the European union in the frame of the ILCD [European Commission 2012].

The composition of the different block is reported in Table 4S (they have been slightly adapted from Table 1 for lightweight non load-bearing block and load-bearing block so to reach 4 MPa and 6 MPa).

The single score has been calculated using the ReCiPe method considering a Hierarchist and Average normalization and weighting set in European conditions [Goedkoop et al. 2012].

The three main expected limitations of this study were(1) that heat and acoustic insulation performances were not considered. The different alternatives were thus not compared on an equal basis; (2) the methodology to estimate nitrogen (NO_3^-, N_2O, NH_3). Despite this was based on the one used in the Agribalyse database for the LCA of French crop production, it has to be kept in mind that this was not developed for permanent crop such as miscanthus; (3) the estimation of the consequences of iLUC could be improved a lot since some rough assumptions were made, i.e., that 1 ha of miscanthus cultivated in competition with food production replaces 1 ha of primary forest. But this last point should not play in favour of miscanthus since it can be expected that less than 1 ha would be replaced.

3 Results and discussion

3.1 Influence of preparation and process parameters (Granulo MG)

3.1.1 Effect of orientation of the blocks during compression tests

During the mold filling and subsequent compaction, the miscanthus fragments can be oriented. In addition, pressure is not homogeneously distributed. As a result, the mechanical properties of the concrete blocks may depend upon the orientation of the blocks during the compression tests. The maximum load sustained by the concrete blocks submitted to axial compression at 0° was 2.4 ± 0.2 MPa while for the blocks compressed in the perpendicular direction 90°, this value is 3.8 ± 0.2 MPa. These results evidenced that the mechanical properties of the test cubes are anisotropic. During mold filling, the miscanthus fibers are flowing in between the movement of sand and cement particles and it can be expected that their mean orientation to be either isotropic or slightly in the filling direction (which is identical to the subsequent the compaction direction). Seen by eye, no specific direction can be spotted at this stage from the blocks' surfaces. But during the compaction, the overall movements of the mix are orienting miscanthus fibers perpendicular to the compaction direction, as can be seen by eye at the surface of the blocks. Fiber orientation in concrete has been widely studied in the case if steel fibers [see for ex Boulekbache et al. 2010; Lameiras et al. 2015; Ozyurt et al. 2007]. The flowability of concrete and its deformation history are influencing the distribution and orientation of the fibers which in turn trigger the mechanical property anisotropy through the intrinsic resistance of the individual fibers and the way crack energy is dissipated. A study of the fiber distribution and orientation inside the blocks was not performed but all blocks were simply marked after demolding in order to always test them in the perpendicular direction at 90°.

3.1.2 Effect of degree of compaction and sand sizes

A set of blocks with weights ranging from 4.2 to 4.9 kg per block, which represents a fresh concrete density of 1220 kg m^{-3} to 1425 kg m^{-3}, was prepared to estimate the optimal degree of compaction. Sand with a granulometry of 0-2 and 0-4 was used to investigate the effect of sand size on the mechanical properties. Increasing the amount of matter to increase blocks' weight increased the difficulty of block compaction. In addition, upon their removal from the mold, the blocks changed their dimensions, especially expanding their height. After 7 days of curing, the obtained blocks were tested for their compressive resistance. The results shown on Figure 2a evidenced the influence of the initial weight of the concrete blocks onto their dimensional stability and compression strength. The size of the blocks after seven days remained nearly stable for the blocks prepared with up to 4.8 kg. But blocks prepared above 4.9 kg showed large dimensional changes. As a result, although the total load sustained was the same as for the block of 4.8 kg, it gave a lower pressure resistance. These results pointed out that for the mode of preparation used, the optimal amount of fresh concrete was 4.8 kg per 15×15×15 cm^3 blocks.

The impact of sand size was also investigated. Figure 2b shows that the compression strength of the blocks was consistently lower when finer sand (0-2) were used for preparation of the concrete. Moreover, the blocks prepared with the finer sand suffered a higher deformation during the curing period than those prepared with the coarser sand. As a result, sand with the granular size of 0-4 was used for all subsequent preparation of concrete blocks.

Figure 2: (a) Relationship between compressive strength/height of concrete block (sand 0-4) after 7 days and its weight (the initial height was 15 cm) and (b) mechanical properties of concrete blocks prepared with sand granulometry of 0-2 and 0-4.

3.1.3 Effect of miscanthus/cement/sand contents

Various mixtures were tested to investigate the effect of miscanthus/cement/sand contents on the compression strength of the obtained concretes (Table 1). The amount of water in the mix is a very important parameter for the overall properties of the concrete matrix. Excess water may induce phase separation and layer formation, while lack of water can reduce the workability and thus limit the compaction. Moreover, unlike mineral reinforcement materials, biomass can both absorb and release different amounts of water depending on their particle size and chemical compositions. In this work, the water-to-cement ratio was adjusted from 0.59 to 1.52 in order to obtain similar consistencies. It can be seen on Figure 3S that although there was only 5 to 12 wt% of miscanthus fibers in the mixture, it accounts for from 30 % to 55 % of the total volume. Thus, the blocks prepared with concrete containing higher amount of miscanthus fibers had to be prepared at a lower density to achieve similar compaction, leading to blocks of 1100 kg m^{-3} to 1475 kg m^{-3} specific masses (Figure 3). The mechanical properties of concrete showed a very clear dependency on miscanthus content. This can be explained by the fact that miscanthus biomass does not have good intrinsic mechanical properties, by the bulk density of miscanthus fragments and its effect onto the volume fraction in the concrete mix. Figure 3 shows the decrease of compression strength with decreasing specific mass of the final concrete, a property observed with other biomass fillers [Waldmann et al., 2016]. Concrete with 12 wt% miscanthus had a compressive strength after 28 days in the order of 2-2.5 MPa. When it was reduced to 9 wt%, compressive resistance improved to 3.5-4.5 MPa and the best results (up to 8 MPa) were obtained for concrete mixes with 5-6 wt% miscanthus fibers.

Figure 3: Compressive strengths vs. specific mass of the concrete blocks after (a) 7 days and (b) 28 days.

3.2 Effect of miscanthus genotypes and sizes (six genotypes)

For testing the influence of miscanthus genotypes and sizes, the reference concrete mix (see section 2.2.2) was used. The water-to-binder ratio varied with the genotypes and sizes of the miscanthus fragments used in the mix, ranging from 0.65 to 0.81. Miscanthus stems cut to 1 cm were used to evaluate the possible effect of genotypes. To suppress the influence of concrete density on the compression strength, the blocks were prepared at the same dry density (1 050 kg m^{-3}, except for blocks reinforced with 3 cm GiGB fragments which was 950 kg m^{-3}, due to the impossibility to compact more without having an immediate deformation of the block).

3.2.1 Influence of sizes and shapes of miscanthus fibers

The effect of fiber sizes was tested only for the GiGB genotype, which was cut to 1, 2 and 3 cm (see Figure 4S).

Figure 4 and Table 3 shows the effect of the length of the fibers on the concrete compression for GiGB. When the length is increasing, the compression strength is strongly decreasing. Figure 4 is also showing the volume change of blocks at 7 days. Increasing the lengths of the fibers was associated with an increase of the volume of the blocks from preparation time till 7 days. This swelling of the blocks is probably due to forces exerted on groups of fibers which are accumulating frozen stresses released with time. The larger the fibers are, the more interactions they have with more possibilities of being out of equilibrium. Using small fibers could thus prevent this effect which is very much affecting the mechanical properties of blocks. Another effect is the ratio of the length of the reinforcing element to the size of the block. The larger this ratio is, the more difficult it is to properly fill the block, which could lead to stress build-up. From the above observation, it can be hypothesized that the differences in both the mechanical performance and dimension stability might lie in the capacity of the smaller fragments to be compacted and fill voids.

Figure 4: (a) Strain-stress curves at 28 days of the concretes reinforced with fibers from different sizes and (b) their compressive strengths at 7 and 28 days (bars) and volume change at 7 days (•).

Table 3: ANOVA table comparing 3 sizes of fragments for *M. giganteus* (coded GIGB in Table 1S) measured at 7 and 28 days (in GPa) and volume change (in %). Means genotype comparisons are based on Student–Newman–Keuls test (SNK) and means followed by a same letter are not significantly different at 0.05 probability level.

Variable		Strength at 7 days (GPa)			Strength at 28 days (GPa)			Volume change (%)		
Effect	Df	F value	Pr(>F)		F value	Pr(>F)		F value	Pr(>F)	
Size	2	56.11	0.001185	*	39.99	0.002269	*	67.94	0.000818	*
Repetition	2	18.87	0.009182	ns	1.26	0.375380	ns	2.34	0.212339	ns
Residuals	4									

Size	Means	SNK groups	Means	SNK groups	Means	SNK groups
1	1.51	a	1.91	a	8.22	c
2	1.38	b	1.51	b	12.56	b
3	1.12	c	1.16	c	14.40	a
Mean	1.34		1.53		11.73	
CV (%)	3.40		6.70		5.69	

* significant at 0.05 probability level
ns = non significant

3.2.2 Influence of genotype on compression strength

Figure 5 and Table 5 show the effect of miscanthus genotype on the compression strength of the blocks keeping length of fibers and density of block constant. On Figure 5a, a difference in the compressive load – deformation curves at 28 days can be seen. For the blocks having the best compression strength (H5, GiGB and Flo), there is a bend at the knee region of the load-deformation curves. For the three other genotypes (Mal, Sac and Gol), the shape of the curve is different, with a plateau up to the breaking point. A similar effect was observed when considering the different fiber lengths, as shown on Figure 4. Miscanthus-reinforced concretes can be considered as a ductile material with miscanthus fibers acting as the reinforcement. The shape with a clear bend at the knee region suggests a better bond between miscanthus fibers and cement matrix, allowing an enhanced load transfer from the cement towards the miscanthus fibers. As a result, the concrete blocks could withstand an additional load at lower deformation levels.

Figure 5: (a) Compressive load – deformation curves at 28 days of the concretes reinforced with fragments from different genotypes and (b) their compressive strengths at 7 and 28 days (bars) and volume change at 7 days (●).

Table 4: ANOVA table comparing 6 genotypes for strength measured at 7 and 28 days (in GPa) and volume change (in %). Means genotype comparisons are based on the Student–Newman–Keuls test (SNK) and means followed by a same letter are not significantly different at 0.05 probability level.

Variable		Strength at 7 days			Strength at 28 days			Volume change		
Effect	Df	F value	Pr(>F)		F value	Pr(>F)		F value	Pr(>F)	
Genotypes	5	100.61	0,0000005	*	114.51	0.0000003	*	87.05	0.0000009	*
Repetition	2	1.28	0,328315	ns	0.42	0.673135	ns	1.19	0.352703	ns
Residuals	8									
Genotypes		Means	SNK groups		Means	SNK groups		Means	SNK groups	
H5		1.67	a		2.03	a		3.77	e	
GiGB		1.51	a		1.91	a		8.22	c	
FLO		1.50	a		1.62	b		6.47	d	
Mal		0.91	b		1.35	c		12.13	b	
Sac		0.46	c		0.80	d		13.70	a	
Gol		0.32	c		0.45	e		12.15	b	
Mean		1.11			1,.0			8.97		
CV (%)			8.72			7.04			7.49	

* significant at 0.05 probability level
ns = non significant

Results of Figure 5 and Table 4 show a clear correlation between the dimensional stability of the obtained concretes and their compressive strength. Concretes with low mechanical performance suffered a higher volume increase during setting, ranging from 12 to 14%. By the opposite, the volume increases for the concretes reinforced with H5, Flo, and GiGB was limited from 3 to 8 %. An explanation for this correlation could be the formation of cracks and internal structural damages in the concrete caused during the expansion of the material before the cement was cured.

During the preparation of the stem fragment from individual *miscanthus* plants, leaf blades, leaf sheaths and stems are separated and mixed up. The leaf blades and sheaths being lighter, they represent a larger volume fraction. As a result, analysis of the fibers evidenced that the *miscanthus* samples containing higher proportions of leave and sheaths presented a lower bulk density than those consisting mostly of stem fragments. Since all concretes were prepared at the similar density, those prepared with the lower bulk density fragments had to be compressed more to reach the required sample dimensions. As a result of this higher compression degree, they might have a larger tendency to increase their size (dimensional changes) to release the stresses accumulated during compression leading to the internal cracks, hence leading to lower mechanical performance. Indeed, as it can be noticed in Figure 5 the evolution of compressive strength at 7 days presents a clear correlation with the bulk density of *miscanthus* fibers used as the reinforcement, with compressive strength increasing with bulk density. Since no fiber selection was conducted, the bulk density of *miscanthus* samples was strongly influenced by the leaf/stem ratio of their individual plants. Thus, the stronger concretes were prepared with the genotypes with higher bulk density (H5, GiGB and Flo) and a lower leaf/stem ratio (Table 2S).

3.2.3 Correlations between density, biochemical composition and compression strength

A comparison between the biochemical composition and the compression strength is difficult since the different genotypes have different densities, linked to the presence of different quantities of leaves. This has a very strong influence on the mechanical properties, as shown on Table 5. The denser genotypes, (H5, GiGB, Flo) have the best mechanical properties compared with the lighter ones (Mal and Sac). The situation for Gol is different, for unknown reasons.

Table 5: Compressive strength (MPa)of concrete prepared with the six genotypes.

Genotype	H5	GiGB	Flo	Mal	Sac	Gol
Leaf/stem ratio	0.04	0.04	0.05	0.22	0.31	0.08
Strength	1.67	1.51	1.50	0.90	0.46	0.32

To compare the biochemical composition of the six genotypes with the mechanical properties of the concrete blocks has no sense if the leaf/stem ratio is not considered. Thus, only the three genotypes having a low amount of leaves was considered in order to keep a group of miscanthus clones with similar structural characteristics. Table 6 gives the correlation results showing that none of the correlation coefficients are significant at the probability level of 0.05. This means that none of the composition parameters has an influence on the compressive strength of the prepared concrete. A plausible reason is that the variation of chemical composition is too low to be effective on cement setting. This result is similar to the only published results on the influence of miscanthus genotypes on concrete properties (Pude et al 2005).

Table 6: Correlation matrix between cell wall (CW) composition and compressive strength for H5, GiGB and Flo. N = 18; ns: non significant at p= 0.05. ABL: Acetyl Bromide Lignin; CA: *p*-coumaric acid; FA: ferulic acid. H, G and S : p-hydroxyphenyl (H), guaiacyl (G) and syringyl (S) thioacidolyis monomers. Rha, Gal, Glc, Ara and Xyl: Rhamnose, galactose, glucose, arabinose and xylose.

Compositional parameter	Strength 7 days	Strength 28 days
Lignin content (% ABL by wt)	0.1 ns	0.34 ns
Phenolic acids ester-linked to the CW		
CA	0.43 ns	0.39 ns
FA	0.1 ns	0.34 ns
Relative % of lignin-derived H, G and S thioacidolysis monomers		
H	0 ns	-0.07 ns
G	0 ns	0 ns
S	0 ns	0 ns
Neutral sugars from hemicellulosic polysaccharides		
Rha	-0.22 ns	-0.13 ns
Gal	-0.2 ns	-0.4 ns
Glc	-0.1 ns	-0.2 ns
Ara	0 ns	0 ns
Xyl	0 ns	0 ns
Total	0 ns	0 ns
Glc from cellulose	0.22 ns	0.13 ns

3.2.4 Effect of light fraction removal

The previous results show that bulk density of miscanthus fibers play a crucial role on the overall compressive strength of the obtained concretes. To corroborate this aspect, a series of tests were conducted in which the lighter fractions of the fibers (leave and sheath pieces) was removed. 1cm fragments from H5 genotype were chosen for this investigation. The reference concrete mix (section 2.2.3) was used, and the water-to-cement ratio was 0.76. The concrete blocks were prepared at the same dry density of 1.05. The influence of sieving (pore size: 5 mm) was also tested, with the separation based on size. It was assumed that considering their strength, the fragments from the stem would remain relatively larger during grinding and thus kept on the sieve. Conversely, the leaves and the weaker parts of the stem might break into smaller pieces and hence, fall through the sieve holes. Figure 5S shows the efficiency of both methods for improving the compressive strength of concrete from 1.67 MPa in the presence of the lighter fractions in the mix and to 2.10 MPa if the lighter fractions were removed by air blown and to 2.73 MPa by sieving. This stresses the absolute need of removing light fractions if willing to prepare blocks with the highest possible compression strength.

3.3 Life cycle Assessment (Granulo MG)

3.3.1 Contribution analysis

Only the contribution analysis of load-bearing block scenario is reported since it is very similar to the two other scenarios. The contribution analysis reported in Figure 6 is performed for a cultivation of miscanthus on a marginal and highly productive land that is not in competition with food production. It does not include the environmental benefit linked to the valorisation of concrete blocks at the end of life, the environmental benefit of carbonation and the carbon storage in miscanthus.

As observed in LCA of hemp concrete [Arrigoni (2017), Prétot et al. 2014, Saez-Perez et al. 2020, Sinka (2018) and Senga Kiessé et al. 2016], the contribution of the binder (mainly cement here) and the transport of the blocks represent the highest contribution to the climate change (more than 90% here). The predominance of the binder production and transport of the blocks is also noticed in the other impact categories (from 40% to 95% and 65% on average). The miscanthus cultivation brings a noteworthy contribution especially on the marine eutrophication (30% to 40% according to the different scenarios) and particulates matter formation (30% to 40%) because of the nitrogen and phosphate emissions related to fertilisation and soil losses. The block end-of-life is noticeable regarding the ecotoxicity of freshwater (20% to 30%) and non-cancerogenic human toxicity (15% to 25%) because of the long-term emissions related to the infrastructure of the sorting plant. Finally, the last step having an important contribution is the infrastructure of block production which represents 20% to 35% of the mineral, fossil, and renewable resources depletion.

Figure 6: Life cycle contribution analysis for a load-bearing scenario block cultivated on a high yield land not in competition with food production.

The influence of the block end-of-life is marginal in most of the impact categories excepted on the land-use (-10% to 20%), water depletion (-10% to 15%) and the mineral, fossil and resources depletion (-10% to 20%) as reported in Figure 7 for the load-bearing alternative. The influence of carbonation and carbon storage on the climate change impact varies between -45% to -70% according to the amount of miscanthus and cement in the different scenarios. The benefit is mainly due to the carbon sequestration in miscanthus (70% to 80%).

Figure 7: Influence of the carbonation, carbon sequestration and co-function on the life cycle impacts of a load-bearing scenario block cultivated on a high yield land not in competition with food production.

3.3.2 Comparisons

3.3.2.1 Non-load bearing scenario blocks

Non-load-bearing blocks have a maximum of 4 MPa compression resistance at specific mass of about 1000 kg m^{-3}. Figure 8 reports the results for all the environmental impacts calculated in this study. The results are normalised to the score of the brick. It means its impact is always set to 100%. If the result of the miscanthus alternative is below 100%, the miscanthus based scenario is better, and vice versa. The type of land used to cultivate miscanthus (high productivity or low productivity land) does not have a major influence on the comparison with the brick except for the marine eutrophication. This is due to the fact that the environmental impacts are mainly generated by the production of the block (50% on average with 28% because of the cement production) and the building of the wall (30% on average with 17% because of the transport of the block to the site and 5% each because of the mortar and the pallet used). Three impacts are in favour of the miscanthus alternatives while eight impacts are in favour of the conventional brick. Thus, unless a significant reduction of the cement use in the miscanthus block production or a reduction of the block weight thanks to a better design to improve structural properties, the miscanthus reinforced block does not seem to be a better alternative compared to bricks for a non-load bearing wall.

It however has to be noticed that the miscanthus block allows a significant reduction of the climate change impact (around -30% for LPL to -40% HPL). Thus, regarding to the specific concern about this impact it has been decided to evaluate the environmental single score using the ReCiPe HA method in order to estimate if the better impact on the climate change can balance the worst results on other impact categories. The results displayed in Figure 9 show that the environmental single scores of the miscanthus alternatives are equivalent to the conventional brick. An eco-design of the miscanthus reinforced block could thus allow to sufficiently improve the overall environmental impact.

Figure 8: Impact comparison of non-load bearing scenario miscanthus concrete block to brick.

Figure 9: Single score comparison of non-load bearing scenario miscanthus concrete block to brick.

Finally, it must be kept in mind that the previous results do not consider LUC. When considering that miscanthus was not cultivated on a land in competition with food for less than 20 years (dLUC scenario), the conclusion is similar. The climate change impact of miscanthus scenarios remain better (-25% for LPL to -35% for HPL) and the environmental single score is equivalent to that of the bricks. However, when considering that miscanthus is cultivated on a land in competition with food production, results are very different. The climate change impact is still better (-5% for LPL to -25% for HPL) but not enough to balance the other impacts and, especially, the additional impact generated by the tropical land use. It leads to an environmental single score 2 to 3 times higher compared to the bricks. Despite the consideration of the iLUC in this study was not fine-tuned, the results show that this fact has to be kept in mind and refined before taking any short-term decision.

As previous studies made on hemp for non-load bearing wall [Heidari et al. 2019, Prétot et al. 2014], this study highlights the importance of not focusing the decision making on the climate change impact only. The benefit of the crop on the climate change impact can be compensated by other impact categories. Unlike previous studies made on hemp, this work questions the development of such an industry without thinking to indirect consequences driven by a global increase of the pressure on food production land.

3.3.2.2 Load-bearing scenario blocks

Load-bearing blocks have more than 6 MPa compression resistance at a specific mass of about 1000kg m^{-3}.

Figure 10 shows that impacts are indeed driven by the production of the block (60% to 70% on average with 37% to 41% because of the cement) and the building of the wall (15% to 20% on average with 11% to 18% because of the transport of the block to the site). The calculation of the single score and the evaluation of the LUC both confirm this conclusion. To be competitive from an environmental point of view, the load-bearing scenario miscanthus based block should: (1) reduce the amount of cement in the formulation (2) and/or modify the type of cement required for a more environmentally friendly one (3) and/or improve the design of the block in order to increase the ratio mass/surface of wall.

Figure 10: Impact score comparison of a load bearing scenario miscanthus concrete block to a 100% concrete block.

4- Conclusions

To produce lightweight load-bearing concrete blocks using miscanthus stem fragments as aggregates in a single mixing method turned out to be impossible, even trying to optimize the concrete formulation, the effect of miscanthus genotypes, the fragment size and to remove light elements like leaf pieces. The results show that genotypes and size of miscanthus fragments play an important role on the mechanical properties of the final products, mainly due to the presence or not of light elements such as leaves and sheath. When comparing genotypes with the same leaf/stem ratio, it was not possible to see a correlation between the biochemical composition of the stem and the compressive strength of the blocks. A probable explanation is the small variation of biochemical composition between genotypes.

Miscanthus-based blocks were compared to conventional alternatives using life cycle analysis tools and the source of impacts were identified in a perspective of eco-design. Although the study must be refined regarding the integration of the heat and acoustic insulation, the first results of the comparison showed that, without improvement, the use of miscanthus block is not competitive compared to conventional load-bearing alternatives (concrete block and lightweight pumice block). However, compared to a non-load bearing alternative (light clay brick), block integrating miscanthus can be competitive from a global environmental point of view thanks to good performances on the climate change impact (-30% to 40%). As previous studies made on hemp showed, this study highlighted the importance of not focusing the decision making on only the climate change impact for developing biobased concretes. The present work also pointed out the risk of decreasing the environmental performances when cultivating the crop on land in competition with food, because of the consequences of indirect consequences of Land Use Change (iLUC), a topic that was not discussed in a previous study about hemp. Finally, the productivity of land (low or high) where miscanthus was cultivated had no major influence on the results excepted when iLUC are considered. Most of the impacts were driven by the use of cement and the transportation of the blocks. However, this LCA study had three main limitations: heat and acoustic insulation performances were not considered, the methodology to estimate was not developed for permanent crop such as miscanthus and 1 ha of miscanthus cultivated in competition with food production replaces 1 ha of primary forest.

An ecodesign of the blocks should thus be oriented on the reduction of cement use as well as on reducing the mass of a block while keeping the same function.

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6- Author contributions

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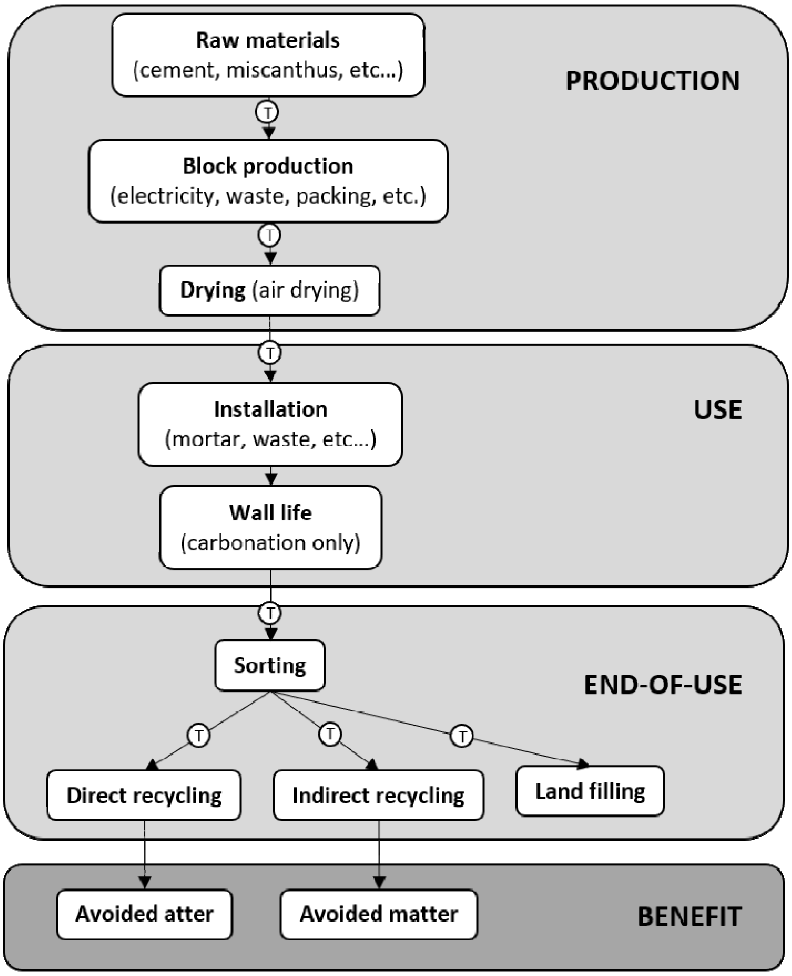


Figure 1: LCA system boundaries.

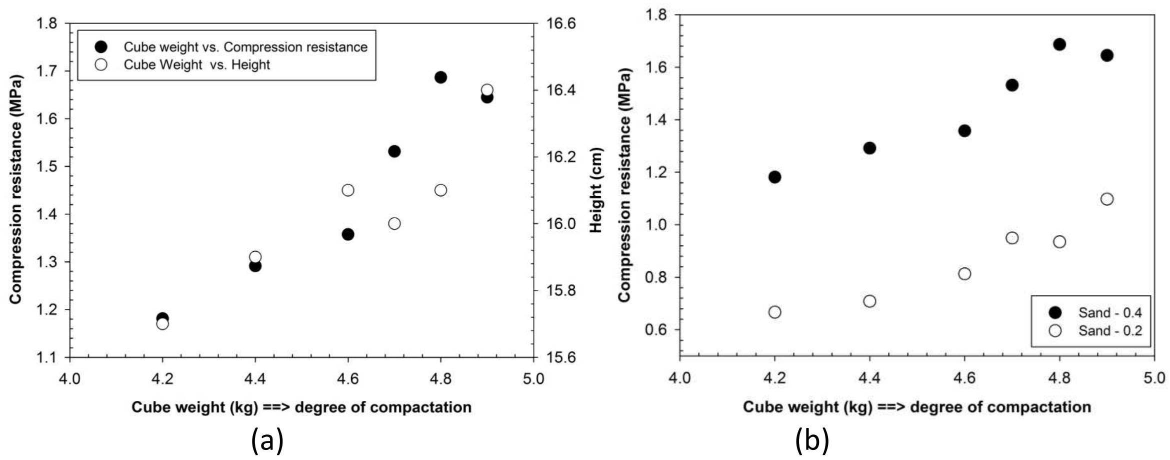
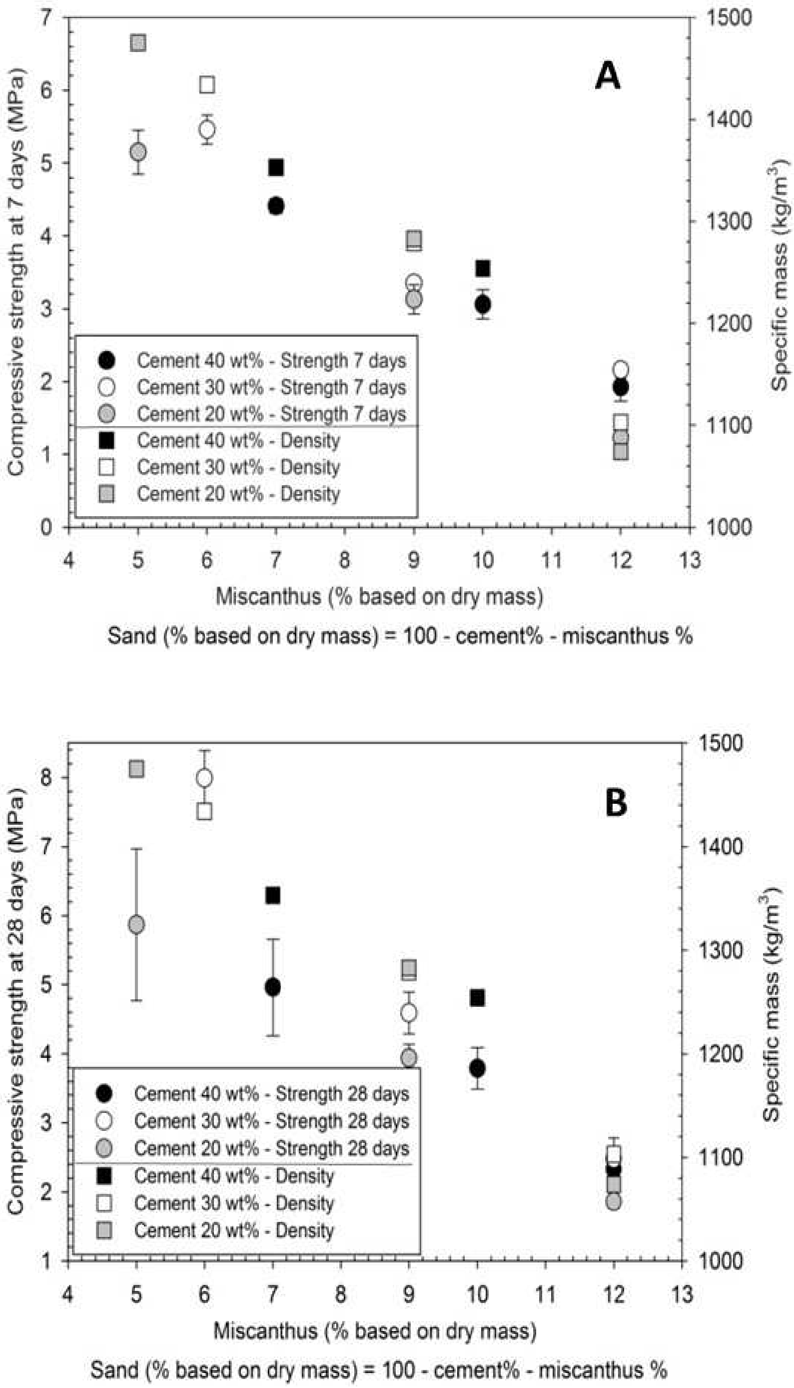
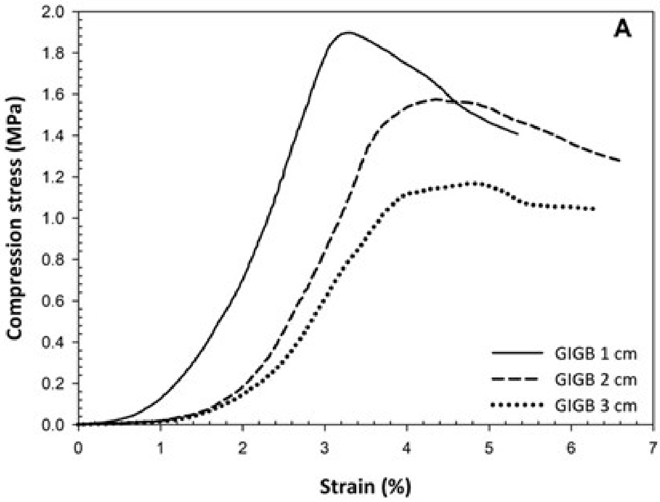


Figure 2: (a) Relationship between compressive strength/height of concrete block (sand 0-4) after 7 days and its weight (the initial height was 15 cm) and (b) mechanical properties of concrete blocks prepared with sand granulometry of 0-2 and 0-4.



<u>Figure 3</u>: Compressive strengths vs. specific mass of the concrete blocks after (a) 7 days and (b) 28 days.



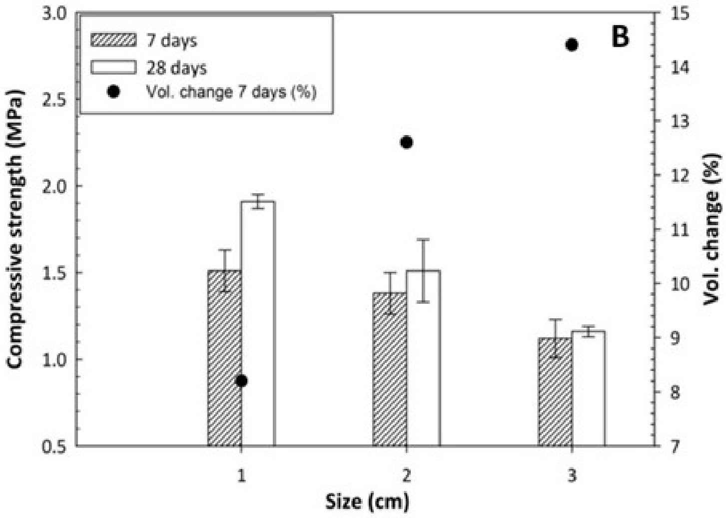


Figure 4: (a) Stress-strain curves at 28 days of the concretes reinforced with fibers from different sizes and (b) their compressive strengths at 7 and 28 days (bars) and volume change at 7 days (•).

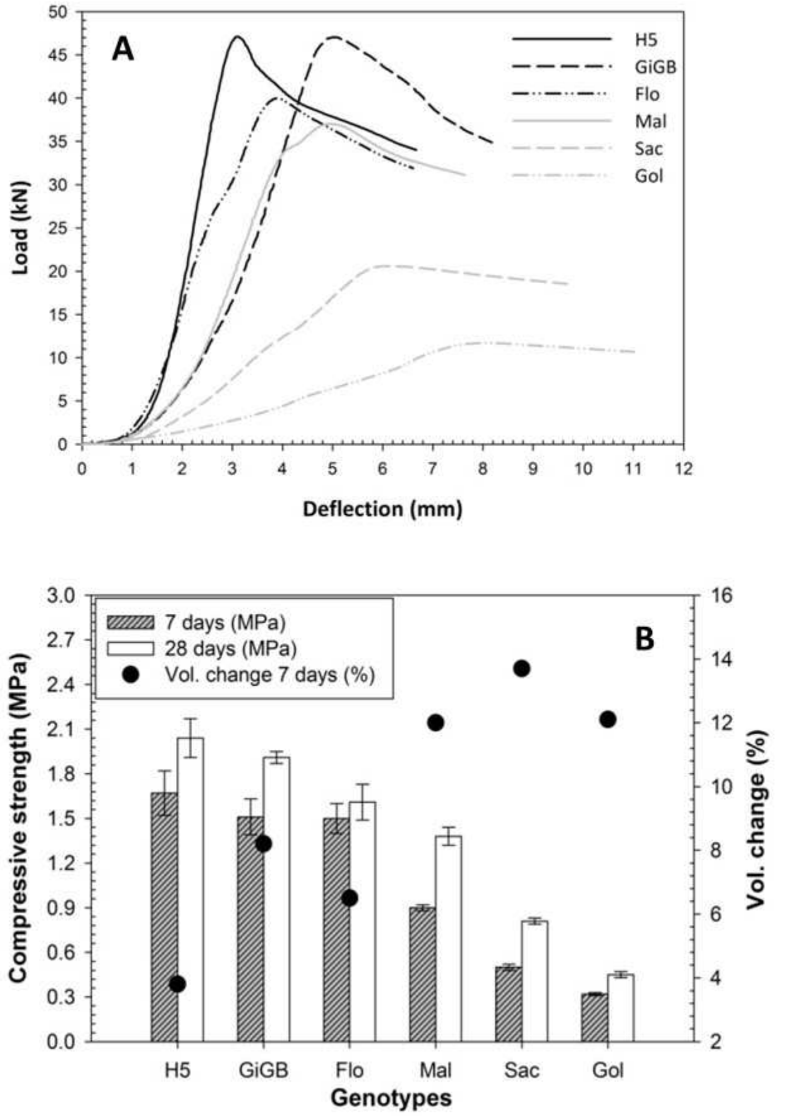


Figure 5: (a) Compressive load – deformation curves at 28 days of the concretes reinforced with fragments from different genotypes and (b) their compressive strengths at 7 and 28 days (bars) and volume change at 7 days (•).

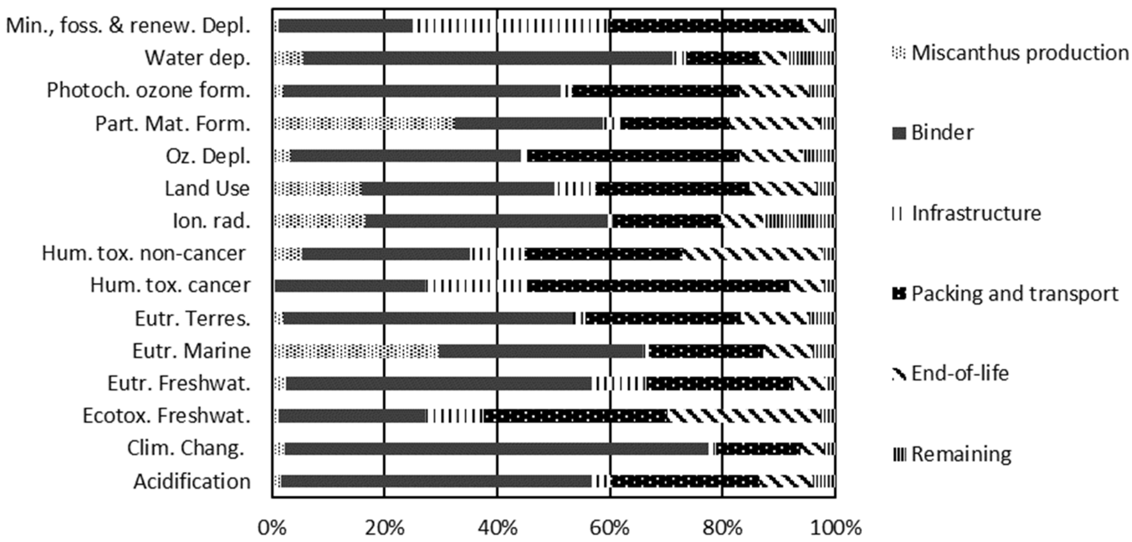


Figure 6: Life cycle contribution analysis for a load-bearing scenario block cultivated on a high yield land not in competition with food production.

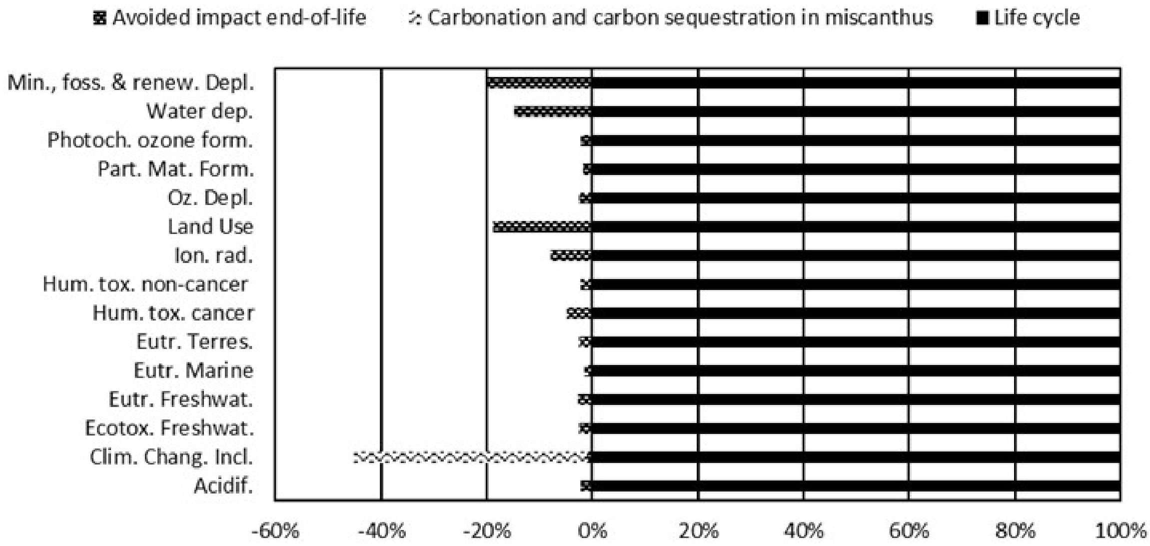


Figure 7: Influence of the carbonation, carbon sequestration and co-fonction on the life cycle impacts of a load-bearing scenario block cultivated on a high yield land not in competition with food production.

a

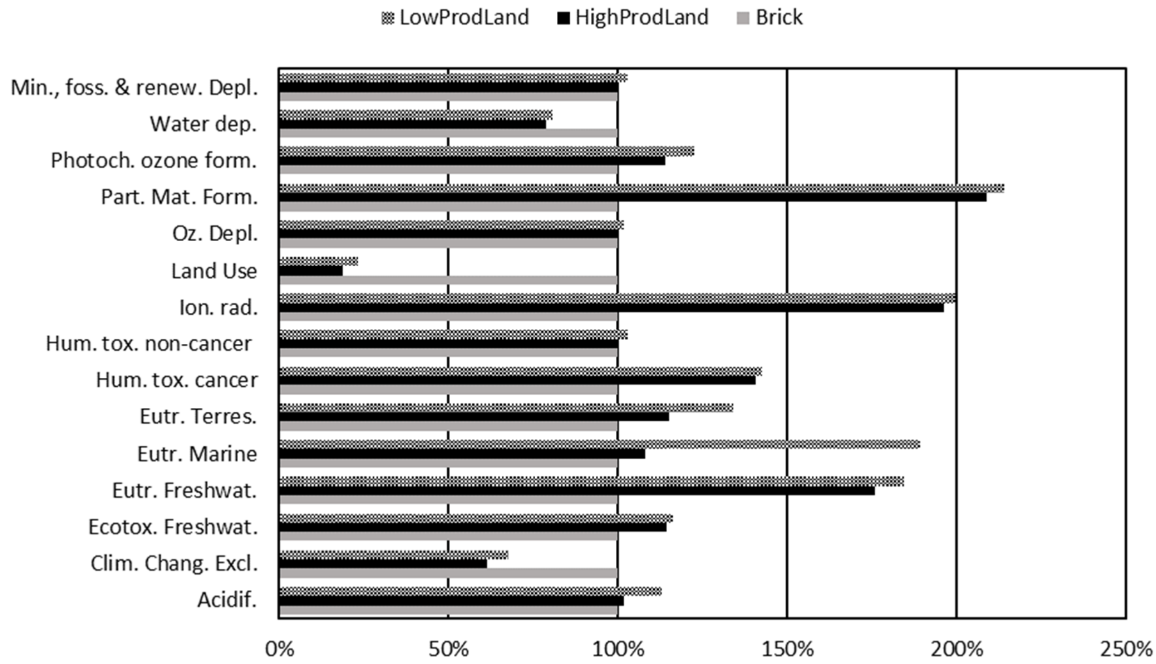


Figure 8: Impact comparison of non-load bearing scenario miscanthus concrete block to brick.

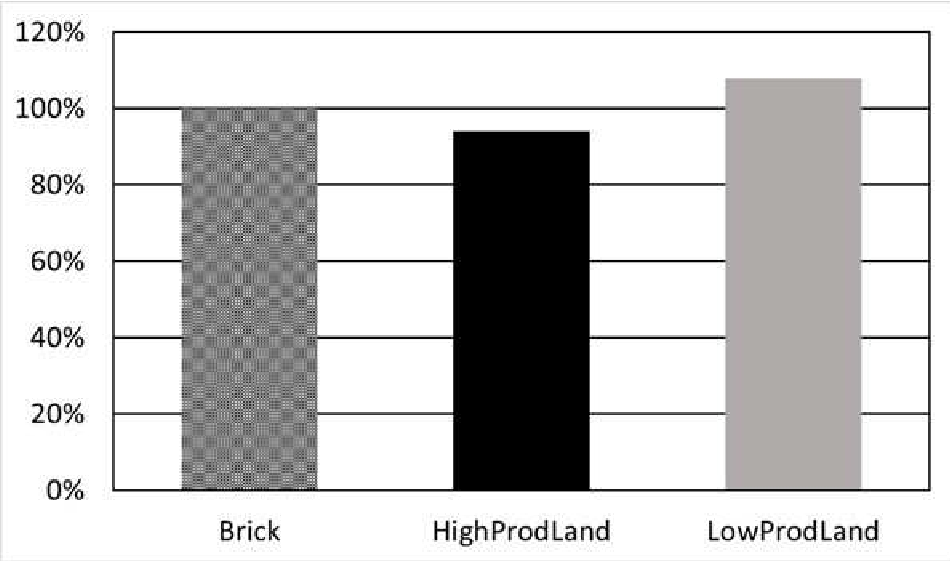


Figure 9: Single score comparison of non-load bearing scenario miscanthus concrete block to brick.

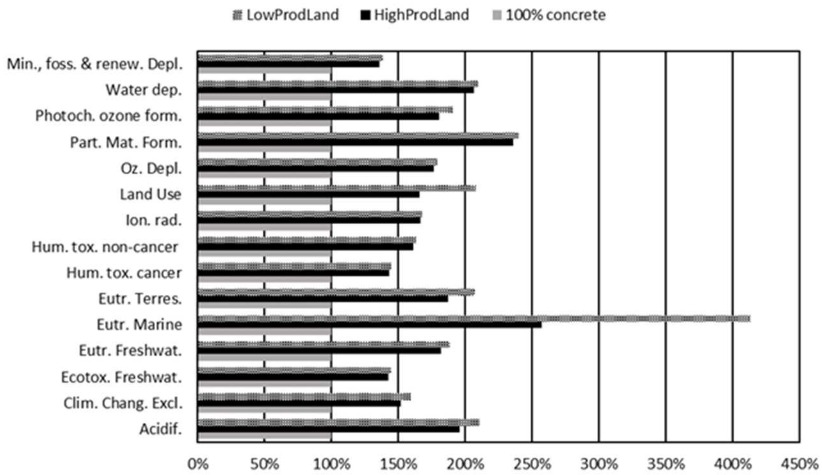
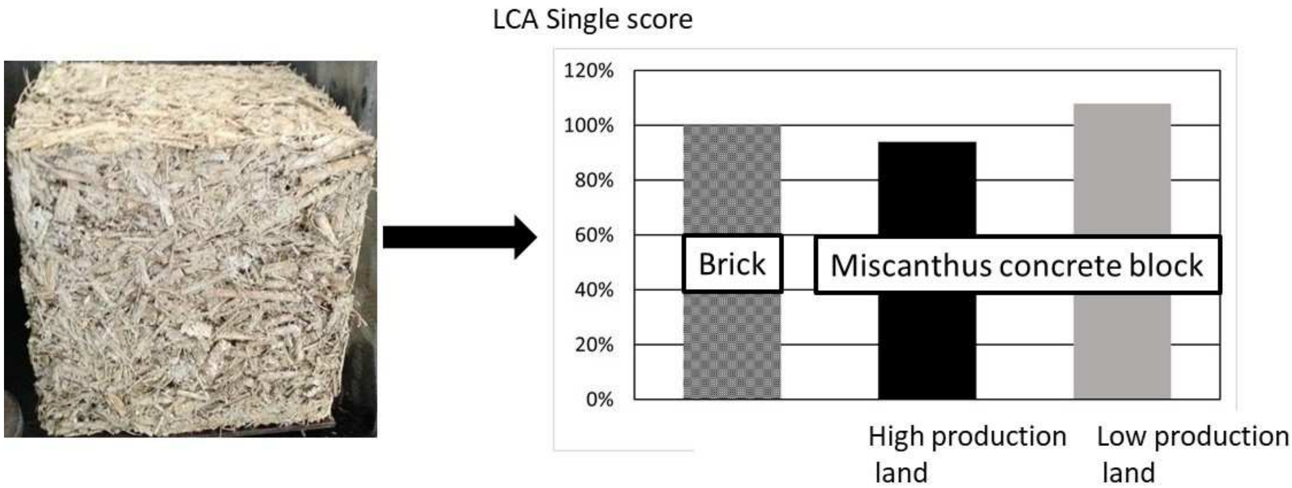


Figure 10: Impact score comparison of a load bearing scenario miscanthus concrete block to a 100% concrete block.


LCA Single score
120%
100%
80%
60%
40%
20%
0%
Brick
Miscanthus concrete block
High production land
Low production land