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Concrete with Organic Waste Materials as Aggregate Replacement

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Abstract: The disposal of high volumes of organic waste is a global issue. Using organic waste instead of sand as an aggregate material for concrete could reduce the strain on waste treatment processes and on the extraction of finite resources. At the same time, it could be a climate change mitigation strategy, by storing the biogenic carbon contained in the organic waste. This project investigated the viability of replacing 10% of fine aggregate in concrete with various organic waste materials, namely rice husk ash, wood ash, corncob granules, and wheat straw. The fresh concrete's properties were studied using the slump test, and the hardened concrete's mechanical properties were measured using the compressive strength and flexural strength tests. In this study, 14 days of curing were considered for the mechanical tests, although the 28-day mechanical strength is more generally accepted. The mechanical performances along with a life cycle assessment (LCA) comparison between the concrete with organic waste and traditional concrete were conducted. The results suggested that rice husk ash and wood ash are the most-suitable organic waste products for use as aggregate replacers considering the mechanical properties. The concrete samples incorporating wheat straw and corncob granules exhibited relatively low strength; unless advanced treatment methods are applied to enhance the concrete's performance, the utilization of these organic wastes in concrete may be limited. The environmental impact assessment of traditional concrete shows that the main contributor to almost every impact category is the production of Portland cement. Sand production contributes only marginally to the overall impact of the concrete. In terms of life-cycle greenhouse gas (GHG) emissions, traditional concrete exhibits the lowest GWP impact per cubic meter when mechanical properties are included in the functional unit used for the comparison. Nevertheless, concrete samples with wood ash and rice husk ash partially offset their lower compressive strength with higher carbon sequestration, showing a similar GWP impact to traditional concrete. This makes them promising alternatives, especially for cases where limited compressive strengths are needed. Further investigations to improve their mechanical properties and optimize their performance are warranted.

Keywords: concrete; organic waste; sand; LCA; mechanical properties

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1. Introduction

The concrete industry is responsible for 5% of the global GHG emissions [1,2] and consumes more raw materials than any other industry [3]. Given the current climate emergency and the limitedness of natural resources, reducing the environmental impact of concrete is a pressing matter.

The concrete industry puts a strain on some finite natural resources, such as sand [4] and water [5]. By substituting sand with organic waste materials, various active and passive advantages can be achieved, such as the mitigation of environmental challenges related to sand consumption, the reduction of costs and environmental issues linked to the amount of organic waste disposal and management, and the possibility to store carbon in concrete through organic waste. Additionally, organic waste can serve as a suitable filler in concrete, with its size distribution closely resembling that of sand, making it a viable substitute. Sand consumption is estimated to be over 40 billion t each year, which is twice the amount of sediment carried by all the rivers in the world annually [6]. Due to population growth, urbanization, and economic development, the global demand for concrete aggregates is expected to increase to 60 billion t per year by 2030 [7], raising concerns about the potential depletion of raw materials. At the same time, the high demand for sand results in illegal mining operations, especially for riverbed sand in developing countries [8,9]. Given the limited nature of sand as a resource and the significant environmental and social impacts of illegal mining, the quest for a sustainable substitute for sand in concrete is of paramount importance. Therefore, the primary focus of this investigation is to identify potential materials that can replace sand in concrete to reduce its environmental and social burden. Agricultural waste is investigated as a possible sand replacement, given its abundance and the necessity to treat it. Incorporating organic waste materials in concrete mixtures not only provides a practical solution to replace conventional aggregates, but also alleviates the environmental and financial challenges associated with waste disposal in a circular economy perspective [10]. Moreover, this approach could hold significant potential in mitigating the effects of climate change by effectively storing the carbon sequestered by the organic waste in the concrete [11]. The problems that the overuse of sand can cause will not just impact the concrete industry. Sand mining from streams, which is the primary source of sand used in concrete, can cause an ecological imbalance [12]. This ecological imbalance is something that is felt globally due to the harvesting of "some 50 billion tonnes of aggregate every year" [13]. The finite nature of sand as a resource combined with the aforementioned ecological and environmental issues with sand collection means that finding a sustainable replacement for sand in concrete is extremely important.

The use of agricultural waste such as corncobs, rice husks, straw, and wood, as an aggregate replacement for concrete has been already investigated in the literature. Memon et al. investigated the use of corncob ash as a replacement for fine aggregates in concrete at different volume ratios (5, 10, 15, and 20%) [14]. The results showed that the compressive strength decreases with increasing the share of corncob ash in the mix. Replacing 10% of aggregates with wheat straw ash has been found to increase the compressive strength of concrete [4]. The use of rice husk ash has been previously investigated as a partial cement substitute in concrete [15]. Gursel et al. compared the mechanical properties and the life cycle environmental impact of different concrete mixtures in which Portland cement was replaced with various percentages of rice husk ash and fly ash [10]. The results showed that the Global Warming Potential (GWP) is reduced when Portland cement is replaced with fly ash and rice husk ash. However, the compressive strength of the ash-containing concrete also decreases; so, only some of the ash-containing samples showed a lower GWP per unit of strength [10]. Unlike these studies, we investigated the use of rice husk ash as a potential aggregate replacement rather than cement. Wood ash has been primarily used for replacing cement in concrete [16,17]. Siddique reported that the strength properties of concrete mixtures only slightly decrease with an increase in wood ash content when partially replacing cement [16].

Prior investigations have primarily concentrated on evaluating the viability and strength of employing specific organic waste materials as substitutes for cement in concrete. In contrast, the present study sought to expand upon these findings by assessing the appropriateness of various organic waste materials as aggregate replacements. The rationale for undertaking this research lies in understanding the role that organic waste materials can play in reducing the environmental impact of the construction sector. Therefore, we conducted a comprehensive analysis encompassing both mechanical testing and comparative life cycle assessment (LCA) studies to evaluate both the mechanical and environmental aspects of these materials' performance.

2. Materials and Methods

2.1. Organic Waste Materials

The materials that were considered in this study to replace sand in concrete were rice husk ash, wood ash, corncob granules, and wheat straw (Figure 1), supplied, respectively, by E-Coco Products U.K., Ebay (Beech timber), The Pest Express, and Gardening Naturally.

Figure 1. Organic waste materials considered in the study as aggregate replacement.

Figure 2 presents the particle size distribution of course and fine aggregate along with four organic waste materials. The organic waste particles have a wider and sharper shape distribution around sand particles. Particle size range was 0.25–2 mm for rice husk, 0.125–0.6 mm for wood ash, 1–0.25 mm for wheat straw (fibers), and 4–0.25 mm for corncob (spherical and cylindrical granules). Additionally, the density of the organic waste particles was slightly higher for rice husk at 1800–2100 kg/m^3 and lower for wood ash at 750–770 kg/m^3, wheat straw at 370 kg/m^3, and corncob at 125 kg/m^3, compared to that of fine aggregate at 1680–1695 kg/m^3. The variations of the physical properties of sand may impact the mechanical properties of concrete.

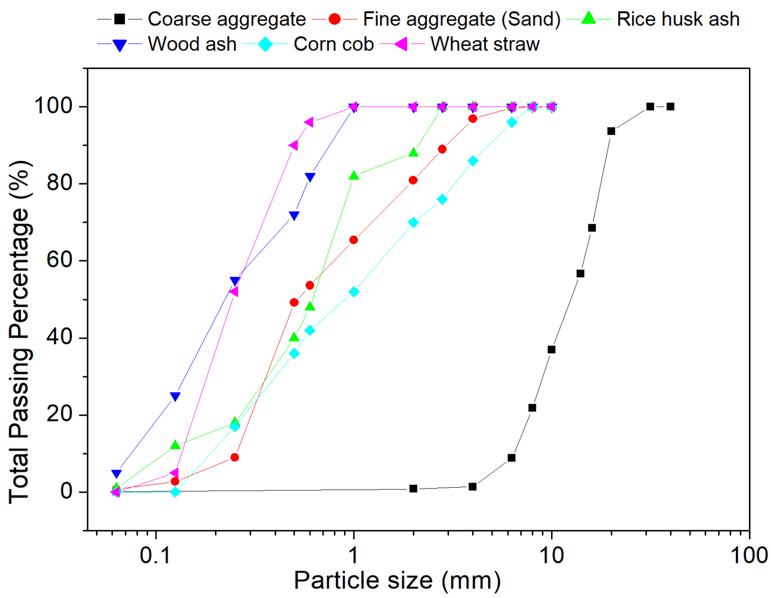

Figure 2. Particle size distribution of aggregates and organic waste materials: rise husk ash, wood ash, corncob, and wheat straw.

The organic waste materials are presented in the following paragraphs.

Rice husk ash is generated by the combustion of rice husk, a byproduct of rice production. When rice is milled to produce rice grains for consumption, the outer shell, known as rice husk, is separated from the grain [10]. Rice husk is usually used as a fertilizer or to produce biochar, while a small part is burned to generate electricity [18]. During combustion, the organic components of the rice husk are burned off, leaving behind the residue, which is the ash [19]. The ash produced is traditionally considered waste, which can lead to environmental concerns if it is disposed of in an open field [18,20]. However, its use is currently being investigated for several applications, like soil improvement, water treatment, and as an aggregate in concrete [18,20]. The residual carbon content in rice husk ash is approximately 5% by weight [21].

Wood ash is readily available worldwide, potentially representing a viable alternative to traditional aggregates. Like rice husk ash, this organic waste is a residue from combustion processes. According to Siddique [16], around 70% of the wood ash generated is sent to landfills, while 20% is used as a soil supplement and the remaining 10% is used for miscellaneous applications. These applications include waste management, where it is used to control odor, and construction, where it can be used as a cement replacement in low- and medium-strength concrete [16]. The high percentage of wood ash sent to landfills makes it an ideal candidate compared to other materials. The carbon content of wood ash varies between 4 and 34% by mass [16].

Wheat straw is what remains in the field when the grain is harvested, and it has several potential applications. The most-common one is leaving it in the field, serving multiple purposes: protecting the soil from erosion, conserving moisture, and facilitating the return of valuable nutrients to the soil as the straw decomposes naturally. Furthermore, wheat straw holds potential in biomass energy production, since it can be directly burned or processed into biofuels. Moreover, wheat straw can be employed as a construction material [22]. Wheat straw has a carbon content of 46.5%, meaning that 1 kg of wheat straw has taken approximately 1.7 kg of CO_2 from the atmosphere during its growth.

Corncob granules are constituted of ground, dried corncob, which is the remaining part of the corn ear after stripping the kernels. Similar to wheat straw, it is commonly left in the field, providing the same benefits mentioned above [23]. The carbon content of this organic waste is close to 50% of its mass [24,25].

2.2. Concrete Mix Design

Ordinary Portland Cement CEM I, 42.5R traditional-grade, supplied by the company Dragon Alfa located in Sharpness, UK, was used as the binder cement. Sands and crushed granules were used as fine and coarse aggregates for each mixture. The sand used was graded as having granules below 4 mm in size. The coarse aggregate grade was between 4 mm and 10 mm in diameter for the granules. The waste materials replacing sand (see Section 2.1) are readily available without the need for further processing, with a particle size of less than 4 mm.

A constant water-to-cement ratio of 0.45 was used in all concrete mixes. A ratio of 1:2:4 was considered for cement, fine aggregate, and coarse aggregate for all of the batches. In Table 1, the composition of the different types of concrete is presented. Traditional concrete, with only sand as the fine aggregate, was used for comparative purposes. The alternative concrete, referred to as concrete with organic waste from now on, had the same composition as traditional concrete, but 10% of the fine aggregate was replaced with organic waste. The preparation of the materials, batching, mixing, and sampling were carried out in accordance with BS 1881 part 125: Methods for mixing and sampling fresh concrete in the laboratory [26]. Concrete cubes (100 × 100 × 100 mm) and prisms (100 × 100 × 500 mm) were prepared and cured in water until testing.

Table 1. Concrete mix composition in 1 m^3.

Scenario	Portland Cement (kg)	Water (kg)	Coarse Aggregate (kg)	Fine Aggregate (kg)	Organic Waste (kg)
Traditional concrete	316	142	1276	704	-
Concrete with organic waste	316	142	1276	634	70

2.3. Testing of Concrete Properties

Both the workability and structural properties of concrete were assessed. For workability, a slump test in accordance with the guidelines outlined in BS EN 12350-2:2019 [27] was performed.

For the structural properties, compressive strength and flexural strength tests were conducted on the concrete cubes and prisms, respectively. The compressive strength test, following the specifications provided in BS EN 12390-3:2019 [28], involved subjecting the 14-day-old cubes to compressive forces to determine their strength. On the other hand, the flexural strength test, in compliance with BS EN 12390-5:2019 [29], assessed the strength of the 14-day-old prisms by subjecting them to bending forces.

The mechanical strength test of the concrete was conducted at 14 days in this study, whereas a 28-day mechanical strength test is more generally accepted. Nevertheless, typically, around 90% of the strength of concrete is gained in 14 days compared to 28 days [30].

2.4. LCA Methodology

2.4.1. Goal and Scope

An LCA comparison was conducted to assess the environmental impact associated with the utilization of organic waste materials as alternatives to sand in concrete production. The LCA was performed using inventory data from the ecoinvent database v3.9.1 [31], with the results calculated using the open-source framework brightway2.5 [32,33].

The impact assessment was performed following the core rules for construction products included in the standard EN 15804 [34]. The impact assessment method considered was EF v3.1 EN15804, which includes 16 impact categories. For the climate change impact, the impacts are divided into 4 categories: biogenic, fossil, land use, and land use change. Investigating the biogenic flows was particularly helpful in our case to assess the carbon uptake from the use of bio-based materials. The process of carbon uptake is also known as sequestration and consists of the capture of CO_2 from the atmosphere during the growth of biomass through photosynthesis [35]. It is worth noting that the default configuration of brightway25 does not account for regionalized biosphere flows. This is especially relevant for the water use impact category, which assesses the potential impact of water consumption on water availability. The reason for this is that the characterization factors can differ based on the specific location where a natural resource is consumed or an environmental flow is emitted. For instance, the characterization factor for the biosphere flow “Water, natural resource” can range from 0 for Greenland to 100 for Aruba. Therefore, for this impact category, we considered the characterization factor specific to Great Britain (3.5 m^3-eq/m^3), assuming that the entire supply chain of the materials included in the concrete takes place in this country.

As for the unit used for the comparison, we first compared the impact of the different mixes on a mere volume basis, using 1 m^3 as the declared unit (DU). Then, in order to include the main function of concrete (i.e., to withstand compressive forces) in the unit used for the comparison, the impacts were normalized for the compressive strength of the different concrete mixes [10,36,37]. Therefore, the considered functional unit (FU) is 1 m^3/MPa.

The system boundaries of the system analyzed are presented in Figure 3. The boundaries included the production of Portland cement, the extraction of sand, the collection of organic wastes, and the production of concrete mixes. Moreover, the extraction and processing of raw materials, energy generation and supply, the utilization of natural resources throughout each stage of the life cycle, and the transportation services required for the concrete ingredients were also taken into consideration. The considered system boundary corresponds to a cradle-to-gate scenario.

The end-of-life stage was not included in this study. Concrete at the end-of-life can be crushed and recycled into new concrete [38,39]; therefore, the biogenic carbon stored in the material does not go back into the atmosphere. However, according to the EN15804 standard, biogenic carbon storage shall not be included in the computation of the climate change impact, even if it is stored permanently [34]. Yet, since one of the goals of this study was to assess the amount of carbon that can be stored in the concrete, depending on the organic waste considered, we decided to include this part in the computation and to assess the biogenic carbon separately. Nevertheless, the carbon content of the materials was included in the datasets developed for the waste. In this way, the potential climate impact of the carbon uptake of the material could be assessed. The carbon contents of the organic waste materials considered are reported in Table 2.

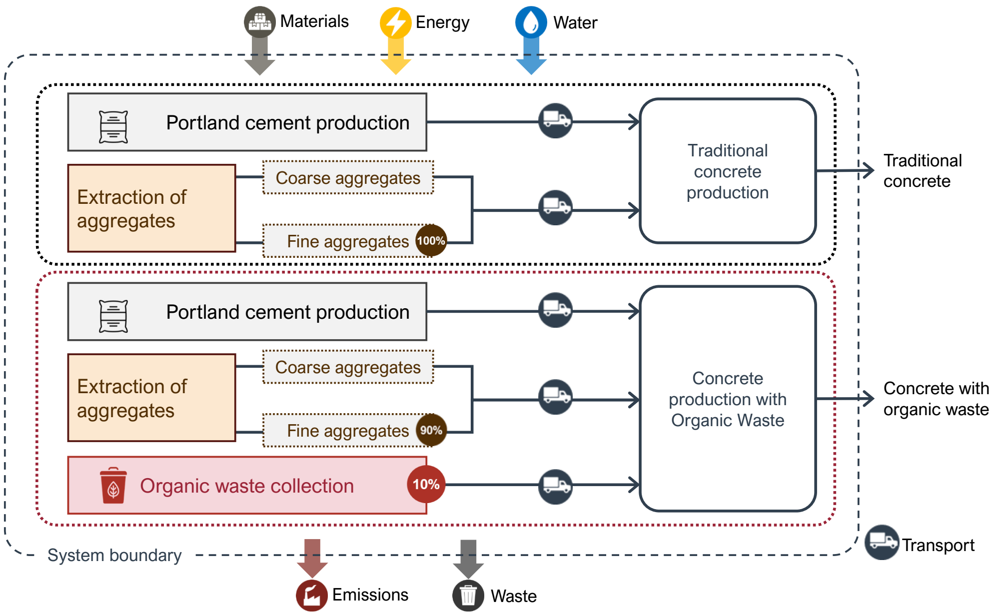

Figure 3. System boundary of traditional concrete production and of the alternative concrete with organic waste.

Table 2. Biogenic carbon content of the considered organic waste.

	Rice Husk Ash	Wood Ash	Wheat Straw	Corncob
Biogenic carbon content (variation)	5.5% (3%–8%) [21]	19% (4%–34%) [16]	46.5% (41.9%–51.1%) [24]	46.8% (42.1%–51.5%) [25]

2.4.2. Life Cycle Inventories

Since the mechanical tests were conducted in Great Britain (GB), we selected datasets representing activities specific to this country. For Portland cement, we relied on the ecoinvent activity “market for cement, Portland” considering “Europe without Switzerland” as the location. Concerning the aggregates, the sand and gravel datasets were considered for the fine and coarse aggregates, respectively. To model these materials, we considered the specific situation of GB. In this country, approximately 22% of the total aggregate requirements for construction are met by dredging sand and gravel from the seabed surrounding the British Isles, while the remaining part is quarried on land [40]. Both inventories for the marine and land aggregates were modeled based on the data provided by the Crown Estate in a report assessing the energy consumption of the extraction of marine aggregates [41]. We then included the water consumption for the two considered sources of aggregates [42]. For the water used in the concrete mixes, we considered the ecoinvent activity “market for tap water” with “Europe without Switzerland” as the location. To model the alternatives incorporating organic waste, we started with the traditional concrete activity and reduced the input of sand by 10%, replacing it with the respective organic waste. Notably, organic waste was directly used to produce the concrete mix without any preprocessing activities. In this way, as a first approximation, we modeled the organic materials as waste, without any burden associated with their production and treatment.

3. Results

3.1. Mechanical Tests' Results

3.1.1. Slump Test

All the concrete samples, but the one containing wood ash, were within a reasonable tolerance for the slump test. The sample with wood ash showed a collapsed slump and was over 200 mm (Table 3). The potential cause for the slump failure of the wood ash concrete sample may be attributed to its limited water absorption capacity. This is possibly owed to its hydrophobic nature and fine particle size relative to the other waste materials. The rest of the samples were between 75 and 105, less than 35 mm from the slump of the traditional concrete sample. Apart from the sample with the wood ash partially replacing sand, the concrete mixes made with aggregate replacers were within 35 mm of the slump of the traditional concrete sample.

Table 3. Slump test results of the concrete samples.

Concrete Samples	Slump Test Results (mm)
Traditional concrete	110
Rice husk ash	90
Wood ash	>200 (collapsed slump)
Wheat straw	105
Corncob	75

3.1.2. Compressive Strength Test

Figure 4a presents the 14-day average compressive strength results of the concrete. The average compressive strength of the different concrete mixes varied significantly. The highest compressive strength was achieved by the traditional concrete.

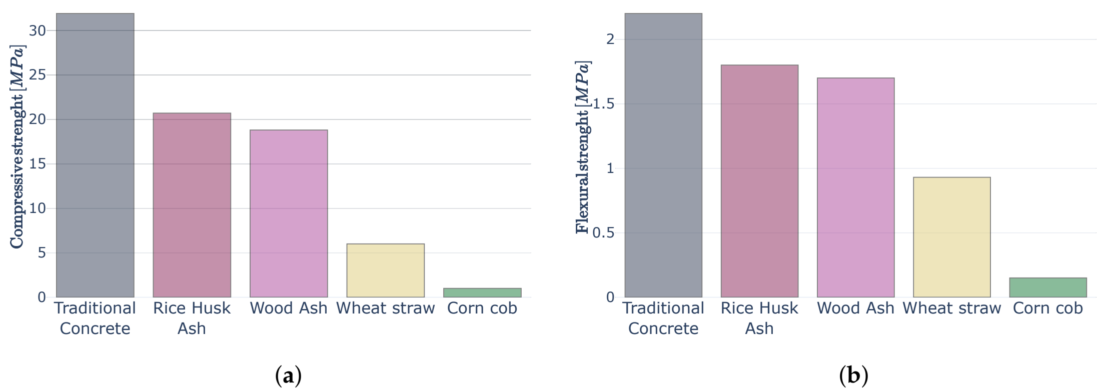

Figure 4. (**a**) Compressive strength test results and (**b**) flexural strength test results for the concrete sample.

As per BS 5328 [43]: for mixes with a grading of 1:2:4 by volume, the compressive strength should be at least 15 MPa at 28 days of curing. The rice husk ash and wood ash concrete exceeded this target after only 14 days. Instead, the compressive strength of the other two samples, i.e., with wheat straw and corncob granules, was well below the target.

3.1.3. Flexural Strength Test

The average 14-day flexural strength test result is presented in Figure 4b. A consistent trend was observed: the rice husk ash and wood ash concrete exhibited comparable flexural strength to traditional concrete. The two ash-based concretes showed even closer alignment with the performance of the traditional concrete samples compared to the results obtained in the compression tests. Rice husk ash performed the best in the mechanical property testing out of any of the concrete mixtures with replaced aggregate. This was evidenced by its average compressive strength at 14 days of 20.7 MPa and average flexural strength of 1.8 MPa. The mechanical properties of the concrete samples made with wood ash were relatively strong; they were only marginally below that of rice husk ash concrete.

3.2. LCA Results per Declared Unit

As this study aimed to assess the environmental advantages resulting from the partial replacement of sand with organic waste as a fine aggregate in concrete, it is essential to determine the role of sand in the overall environmental impact of the traditional concrete mixture. The traditional concrete results for each impact category of EF 3.1 EN15804 are reported in Figure 5. The main contributor for every impact category, but water use, is the production of Portland cement.

The impact caused by fine agg is quite limited, with a contribution to the overall impact varying from 3.5% for the impact category metal and mineral resources to 27.4% for water use. Reducing the amount of fine aggregate by 10% can achieve a reduction for the water use impact category of 2.74% and 0.43% for climate change. Nevertheless, when carbon uptake is taken into account, substituting it with organic waste can be a relevant mitigation strategy to further reduce the impact of climate change, thanks to the biogenic carbon stored in this waste. Given that the impact of sand on the overall impact of concrete in all categories is very limited and that no impact is assigned to the waste materials, the focus of the analysis was limited to the climate change category.

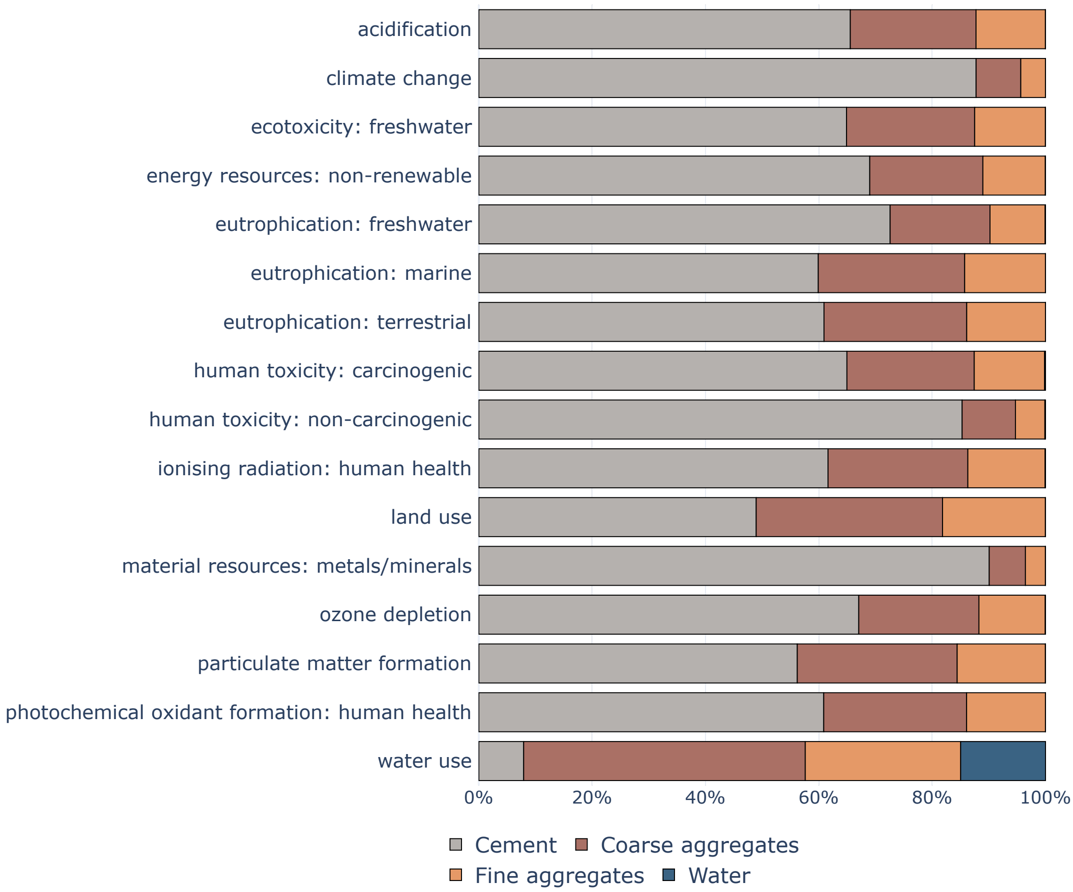

Figure 5. LCA results of the traditional concrete: breakdown of the contributions from concrete ingredients in traditional mix.

The comparison of the different concrete mixes for the climate change impact category is shown in Figure 6. The results indicated that concrete alternatives incorporating organic waste exhibited lower environmental impacts compared to the traditional mixture per cubic meter (i.e., the DU), thanks to their biogenic carbon content. The concretes involving corncob and wheat straw demonstrated the most-substantial reduction, achieving a decrease in impact compared to the traditional concrete of 36.5% and 36.2%, respectively. This is due to the higher carbon content of these organic wastes. Moreover, Figure 6 shows, for each concrete sample, the variation in the potential climate change impact as the carbon content changed. A greater variation was associated with wood ash, since the carbon content may vary significantly [16].

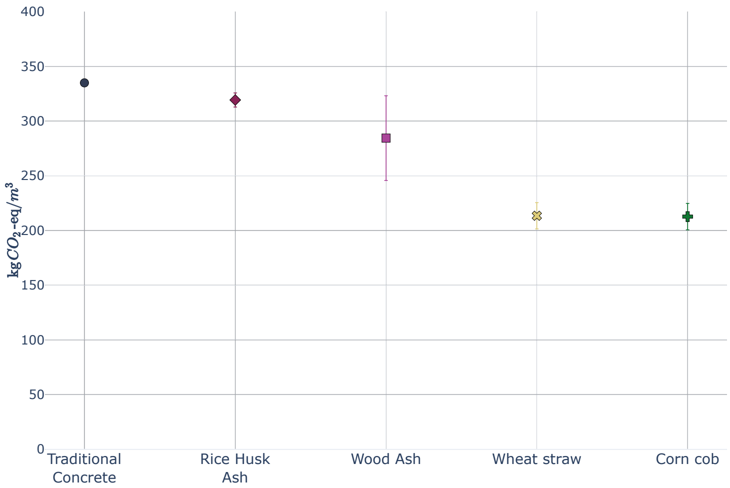

Figure 6. LCA results per functional unit for the climate change impact category. The error bar indicates the variation due to the uncertainty of the carbon content in the organic waste.

LCA Results per Functional Unit

For a comprehensive evaluation of the concrete mixes, the climate change impacts were divided by their mechanical strength, considering the results obtained in the compressive test. The outcomes are reported in Figure 7, where the bars represent the compressive test results, while the red line represents the GWP impact at equal compressive strength. The best concrete mix resulted in being the traditional concrete, due to its better mechanical performance. However, the concrete samples including rice husk ash and wood ash had a GWP impact comparable to the one of traditional concrete. The worst results were associated with the concrete mix with corncob due to its poor compressive strength.

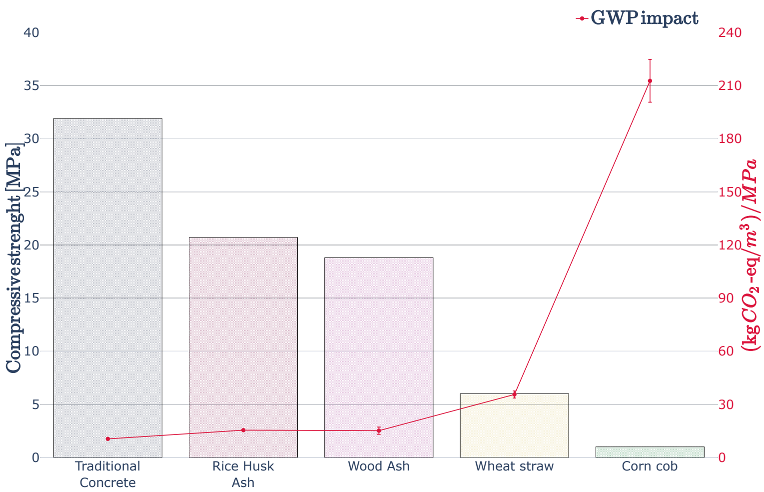

Figure 7. LCA results per functional unit. The bars indicate the compressive strength results, while the red line shows the GWP impact. The error bars display the variation due to the biogenic carbon content of the organic waste.

It is important to point out that the FU considered does not take into account the specific application the concrete might be used for. For instance, if the application required a compressive strength of only 15 MPa, different results could be obtained.

4. Conclusions and Future Developments

This study presented an initial attempt to assess the mechanical properties and the environmental sustainability of partially replacing sand in concrete with four different organic waste materials, specifically rice husk ash, wood ash, corncob granules, and wheat straw. The environmental impact of sand is much lower than cement in concrete. However, the replacement of fine aggregates with organic waste could represent a potential mitigation strategy to further reduce the climate change impact of concrete, thanks to the carbon stored in the waste. Both addressed aspects are important; in particular, concrete strength is fundamental in order to evaluate the suitability for a specific application, i.e., the functionality of the concrete, while the aspect of storing carbon is paramount in a global warming mitigation perspective, at equal functionality.

Notwithstanding the credit for storing carbon, traditional concrete appears to be the most-sustainable solution when the mixes are compared per unit of mechanical strength (i.e., (kg CO_2-eq/m^3)/MPa). However, the wood ash and rice husk ash samples showed similar GWP impacts, positioning them as promising alternatives for further study.

Additional research is necessary to establish these materials as viable alternatives:

1. A thorough investigation into the actual carbon storage at the end-of-life of concrete is essential. This requires exploring potential end-of-life scenarios to comprehensively assess the impact of these concrete mixes;
2. While this study focused on the climate change impact category, the impact of using organic waste in concrete should be investigated more in detail for other environmental impact categories as well. The potential reduction in water consumption would be extremely important to investigate given the large water footprint of sand. In our study, we assumed that waste carries zero burden with it. However, if the waste is used in concrete, it could become a valorized co-product. Therefore, more research is needed on how to allocate the water consumed by the crop (and the other environmental impacts) to the products;
3. Integrating a consequential life cycle assessment (LCA) is endorsed to evaluate the broader implications, encompassing economic, social, and environmental aspects, including the potential trade-offs in using organic waste for different purposes [44]. Moreover, it could be important to carry out a social LCA to understand the implications of illegal mining of sand;
4. Further laboratory investigations are recommended to optimize the mechanical properties of concrete using organic waste. In particular, it is recommended to understand the evolution of the mechanical properties and durability of concrete with different organic waste replacement rates and consider longer curing times. Indeed, in this study, 14-day mechanical strength tests were performed, whereas a 28-day mechanical strength is more generally accepted. Furthermore, an extended observation period is recommended to assess the potential deterioration of organic waste particles within the concrete matrix.

Supplementary Materials: The following Supporting Information can be downloaded at: https://www.mdpi.com/article/10.3390/app14010108/s1. Table S1: LCI of the traditional concrete. Table S2: LCI of marine sand and gravel extraction (Kemp, 2008) [41]. Table S3: LCI of land sand and gravel extraction (Kemp, 2008) [41]. Table S4: Characterization factors of the biosphere flows according to the impact assessment method EF 3.1 EN15804, considered to compute the water use impact. Table S5: LCA results of the traditional concrete's ingredients. Table S6: LCA results for climate change impact category for the concrete samples.

Author Contributions: Conceptualization, T.Q. and D.S.; methodology, T.Q., D.S., N.B. and A.A.; software, N.B.; validation, T.Q., A.A. and G.D.; data curation, T.Q., D.S. and N.B.; writing—original

draft preparation, N.B. and T.Q.; writing—review and editing, T.Q., A.A. and G.D.; supervision, T.Q., A.A. and G.D. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

DU	Declared unit
FU	Functional unit
GB	Great Britain
GHG	Greenhouse gases
GWP	Global Warming Potential
LCA	Life cycle assessment

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