Cross-Fertilization Between Architecture and Agricultural: A Circular Supply Chain

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Abstract. The construction industry in Europe seems to be in a state of decline, actually at a broader level it is a sector in full development. A development to be related to paradigm shifts from linear to circular economy. The latest policies and standards are in fact focused on accelerating such transition.

Enterprises are working to change their manufacturing processes, particularly are interested in developing - often in cooperation with research centers - more ecofriendly building materials.
In this context, the research project ECOFFI aims at investigating the cross-fertilization opportunities between apparently incompatible sectors - the agrifood and the construction - for manufacturing a new building material.
The paper deals with some activities carried out, including experimental and monitoring phases. Finally results from a life-cycle study based on embodied energy and embodied carbon indicators of samples is even shown.

Keywords: Recycling, Agricultural waste, Corn cob, Rice straw, Lightweight concrete.

1 Introduction

1.1 Building and Circular Economy

The construction industry in Europe seems to be in a state of crisis although there are some improvement signals. This, however, does not cover the accumulated losses of over 10% since the financial crisis in 2009 [1].

In a broader perspective, it is a sector in full development. The Global Status Report 2017, describes how over 230 billion square meters of new buildings are expected to be built over the next 40 years [2].

A growth confirmed by the sector's continuing impact on a worldwide scale. The buildings and construction sector accounted for 36% of final energy use and 39% of energy and process-related carbon dioxide (CO_2) emissions; 11% of which resulted from manufacturing building materials such as steel, cement and glass. Decarbonising the buildings and construction sector is critical to achieving [3].

On the whole, the production of materials and components for buildings is associated with a constant increase in CO_2 emissions, which have risen from 3.1 Gt in 2010 to 3.7 Gt in 2016.

The European Commission recalling a principle of responsibility connected to sustainability, to reduce resource use and emissions realises, affirmed it is necessary applying Circular Economy and resource efficiency principles to the construction sector [4] [5]. The Commission has proposed a new and ambitious package to update the current legislation [6], and the issue of the CE is already evolved and mature both in the scientific literature [7] [8].

Reducing waste and facilitating their high-quality management thus becomes a key objective. This includes the reuse or recycling of secondary raw materials and byproducts coming from other manufacturing sectors [9]; in this regard, the current [10] and future [11] research and funding programmes are structured to promote the transition to a circular model by encouraging cross-fertilization between different industrial sectors.

Finally, some existing indicators can help to measure the Circular Economy performances. Embodied Carbon (EC) and Embodied Energy (EE) as defined in life cycle based standard and references [12] [13] are useful in assessing the energy efficiency of a recycling process and the avoided environmental impacts.

1.2 International scientific research about recycling of agricultural by-products

In Europe, sustainable waste management is a mature and developed issue, starting with the regulatory framework. Directive 2008/98/EC [14] sets as a priority objective the activity of use, recycling, and waste reduction; it also proposes a model in which it is appropriate to identify and develop, for different categories of waste and by-products, collection activities and inclusion in virtuous recovery and recycling cycles.

At the same time as the current regulatory framework, there are several scientific publications oriented to the development of building materials through the recycling of agro-food waste such as sugar beet pulp and potato starch [14], wine waste [15], rice husk [16], coffee husk [17], sugarcane bagasse ash [19], moss, rye straw and reed [20].

In this R&D field, it acts TeAM's (Technology and Environment) research team. The group works at the Department of Architecture and Design (DAD), Politecnico di Torino; TeAM has been working for more than 10 years at developing innovative building materials and components featured by low environmental impacts and made with waste and by-products [21].

1.3 ECOFFI project: objectives and synthesis of activities

"Ecological COncrete Filled FIbers" (ECOFFI) is research that was aimed at developing a circular model concerning the use of local resources - agricultural residues - potentially available and currently under-exploited in the production of lightweight concrete conglomerates. The project was carried out within a cooperation program between European Regions (Piedmont - Italy and Rhone-Alp - France), in which Politecnico di Torino and Small/Medium Enterprises (SME) participated.

Particularly VICAT Group is a french medium enterprise leading in cement production while Sarotto Group is an italian small enterprise manufacturing lightweight concrete blocks.

The research was carried out through stages.

Initially, in order to assess the availability and the feasibility of the re-use of agricultural by-products, piedmontese crops were surveyed. It emerged that the greater quantities of residues produced annually were from corn and rice cultivation.

The by-product from the harvesting of corn is the corncob (the portion of cob in which the grain is grafted) while by the operations of threshing of rice, straw consisting of the stem is produced, and from the foliar apparatus of the plant (see Fig. 1).

In the second stage, by-products were tested within the cement mixture. A certain number of samples were produced to get a cohesive mix design to be compared with other lightweight concrete.

In the final stage, once set out the concrete block volume and size: 1) the performances (thermal and mechanical) were monitored; 2) the environmental impact of 1 m^2 of the wall system was assessed through a Life Cycle Assessment (LCA) based study.

Finally, at the end of the ECOFFI block life cycle study, the results were compared with similar materials to understand the potential of the new plant-based mixture.

a) b) c) d)

Fig. 1. (a) Maize plant, (b) Corn cob, (c) Rice plant, (d) Rice straw

2 The agricultural waste recycling scenarios

To design a circular agricultural model for the recovery and recycling of by-products, to be applied at a local level, it is basic to know their quantity and quality as well as their disposal methods.

In this stage, it was crucial the analysis, in the Piedmont region (I), about the availability of by-products of agricultural waste; equipment for collection and storage operations; transportation modes; potential revenue generated by recovery processes (Tab.

1). Table 1 shows that in Piedmont the area cultivated with maize and rice [22], differs by about 24.000 ha. A deviation that however has limited effects on the estimated by-products calculated by multiplying the area under cultivation for the value of the yield per hectare referred to by-products themselves (measured in t/ha). To this substantial equivalence of potential, there are no similar quantities of waste sent for recycling processes.

Table 1. Real and estimated synoptic picture of the collection and sale of maize and rice by-products in Piedmont [Author processing]

Piedmont Region	Maize cultivation	Rice cultivation
By-products	Corncob	Straw
Cultivated area of main product [ha]	140.366	116.324
By-product yield per hectare [t/ha]	1,3	3
Potential annual availability [t/year]	182.475	174.486
Recoverable quantity [t/year]	7.000	739,5
By-product harvest equipment	Combine harvester and Harcob equipment	Round-baler
Selling price (euro/t)	60-70	45-70
Potential revenue (euro)	455.000,00	42.188,50
Average distance from the concrete production site [km]	50	100

Nowadays in Piedmont, corn cob is used as biogas; recycled in the production of bedding animals; used in the industrial sector for metal cleaning. Nonetheless, the equipment currently available does not permit the recovery of the entire quantity of agricultural by-product potentially usable (182.475 t).

The survey carried out within ECOFFI project was identified two potential enterprises able to increase the current amount of by-products:

- Consorzio Agricolo Piemontese per le Agroforniture e Cereali (CAPAC), which is equipped with Harcob kit[1] and it is able to pick up 14.000 t/year of the corncob, 50% of which could be allocated to other sectors, including the construction one (7.000 t/year).
- The enterprise Agrindustria Tecco s.r.l. (Cuneo), which has spaces and equipment for the storage, drying, and sieving of the corncob.

[1] The Harcob kit is an auxiliary equipment for combine harvesters, developed within the "Enecob" project financed by the Piedmont Region (PSR 2007-2013), which allows simultaneous harvesting of maize grain and cob, limiting harvesting time and costs.

Rice straw crop residues are now recovered in the livestock and bioenergy sectors in limited quantities (about 10% of the total). This is due to the high silica content (130.000 mg/kg). A physical characteristic that makes the by-product unsuitable for recycling in the agricultural sector, but which could be exploited in other industrial processes, particularly in the construction sector. To determine the availability of a harvest cycle calculated every two years. It was estimated 3 t/ha dry matter (prudential approach to not compromise the soil organic matter reintegration) [23]. The resulting potential residue availability is 174.486 t/year.

For the cutting operations, ECOFFI proposed the recycling of rice straw through the involvement of some farms; for the harvesting, instead, the rice straw is collected by a contractor equipped with a round baler. From a single round baler (10 t/h) it is possible to store up to 870 t/year of straw; it was estimated a 15% loss (loss physiological aspects of transport and first processing operations), while it was approximately predicted a production of 739,5 t/year[2]. The bales are transported to one of the SMEs taken part in the ECOFFI project (Narzole, CN), where the rice-stems, with the aid of a mill shredder, are finely chopped (length of 2-10 cm).

3 An ecological mix-design with corn-cob and rice straw

3.1 The experimental stage

The estimation of the by-product quantities and the definition of the recycling processes involved went hand in hand with the testing stage.

In the ECOFFI project such a stage was characterized by the production of 34 samples.

The following ingredients were used for the mix-design: Prompt natural cement[3] [24]; water, citric acid (setting retardant); corn cob (aggregate) and rice straw (fiber). The quantities of the first three ingredients were unchanged, while the quantities of by-products were varied. The decision to use a natural hydraulic binder, instead of ordinary cement, comes from the specific requirements of the enterprises involved in the project. The development of the mix-design was divided into three series of tests (as displayed Fig. 2).

The first series was conducted using only the natural corn cob taken from the field[4] with a grain size between 1-40 mm, which also contains pieces of pruning mowings of corn cob. In the first experimental work, it was decided to test the aggregate alone, to evaluate its performance independently from rice-straw. The natural corn cob is

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2 The annual useful hours available for straw packaging have been estimated as an average of 5 years equal to 87 hours for year (2013-2017) based on Regional Environmental Protection Agency data (ARPA).

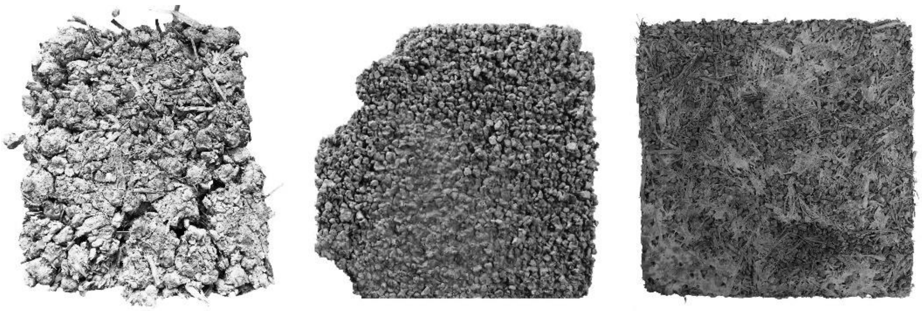
3 Prompt natural cement is a natural hydraulic binder produced by Vicat Group

4 The natural corn cob is harvested from the field, separated from the grain and chopped up by combine harvesters. It is then transported by means of wagons to be stored in horizontal trusses or vertical silos. In the storage phase the natural cob is loaded in layers and compressed by weights, to reduce the presence of air, the development of yeasts and moulds.

characterized by a moisture content of 41%. To use it in a cement mixture, it was necessary to dry it naturally with the aim of reducing the moisture content to 28%. As shown in Fig. 2-a the 4 samples carried out had cohesion problems due to the non-uniform grain size.

In the second series of tests, the natural corn cob was replaced by the industrial corn cob[5] (average humidity: 13%) in two different grain size classes (0,85-1,04 mm and 2-6,3 mm) which were sieved to distribute the granules in the mixtures. However, the 20 samples produced still showed a poor cohesion (Fig 2.b). In this case the expansion and withdrawal of the aggregate was caused by the sample's hygroscopic behaviour. It was, therefore, necessary to add some fibers in the mix-design since they are capable of filling the interstices among granules.

Based on the results obtained, it was finally decided, in the third experimental series, to mix the aggregate with a grain size between 2-6,3 mm (50%) with a fiber consisting of chopped rice straw with a length between 2-10 cm (50%). The fiber filled the gaps in the samples and made it possible to package 10 cohesive samples (Fig. 2-c).



a) b) c)

Fig. 2. Difference in cohesion between the aggregates used in the three phases. a) Natural corn cob, b) Industrial corn cob, c) Industrial corn cob and rice straw.

3.2 Monitoring and eco-compatibility assessment phase

On the last series of samples (fig. 2-c) monitoring were carried out to assess the bulk density, compressive strength, and thermal conductivity.
The following standards were used:

- EN 772-1:2015: Methods of test for masonry units - Part 1: Determination of compressive strength;

5 The process of industrialization of the corn cob can be summarized in four main steps. Harvesting of the drums left in the ground after separation from the grain, drying of the corn cobs by means of a biomass fired boiler, grinding of the dried drums, sieving in different grain sizes and storage in bags

- EN 12664:2002: Thermal performance of building materials and products - Determination of thermal resistance by means of guarded hot plate and heat flow meter methods - Dry and moist products of medium and low thermal resistance.

Table 2 shows the results achieved. The bulk density analyzed on the samples demonstrates an average result of 540 kg/m^3.

With regard to mechanical performances the samples tested have an average characteristic strength (Rck_m) of 0,5 MPa.

The thermal conductivity (λ) was calculated on 3 samples at the DENERG (Department of Energy) laboratories of the Politecnico di Torino. The average U-value determined is 0,088 W/m^{2}K.

According to Italian climate zones requirements[6], a further analysis was carried out. Defining the sample size that it should have in order to meet the requirements in Italy's coldest climate zones (E and F). The chosen length of sides was 20 x 30 x 40 cm. The thermal transmittance was calculated for the side with a length of 40 cm (U_{40cm} = 0,22 W/m^{2}K).

Table 2. Results of monitoring and LCA study of the ECOFFI block [Author processing]

Symbol	**Parameter**	**Unit of measure**	**Value**
ρ	Bulk density	kg/m^3	540
Rck_m	Compressive strength	MPa	0,5
λ	Thermal conductivity	W/mK	0,088
U	Thermal transmittance (40 cm block)	W/m^{2}K	0,22
EE	Embodied Energy	MJ/m^3	1279,8
EC	Embodied Carbon	$kgCO_{2eq}/m^3$	191,7

In addition to the monitoring activity, LCA based study was carried out to measure the main input flows (raw materials, by-products, energy resources, etc.) and output flows (finished product, wastes, and emissions) to evaluate the environmental impacts.

Following the methodological framework of the LCA study [25] and taking into account the legislation on Environmental Product Declarations (EPD) [26], it was decided to adopt two parameters: Embodied Energy (EE) and Embodied Carbon (EC); described in UNI EN 15978:2011 [12]. EE (MJ) is the amount of primary energy consumed through the use of building materials, products and processes, along with related transportation. The following energy processes were accounted for: extracting and processing of raw materials and byproducts; manufacturing of construction materials; transportation and distribution. LCA methodological approach known as "from cradle to gate". EE is directly related to Gross Energy Requirements (GER).

6 Ministerial Decree 26 June 2015, Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli edifici;

Embodied Carbon (kg CO_2eq) is the carbon equivalent emitted from the processes of materials extraction and manufacturing, including transports, construction and final disposal (see EE). EC is equivalent to the greenhouse effect characterised by weighting factors, namely the Global Warming Potential calculated on a time reference established over 100 years (GWP100).

Furthermore, the choice of EE and EC parameters is to be considered significant in the construction sector to assess the impact of construction products, as specified in Annex 57 of the International Energy Agency in Buildings and Communities programme (IEA EBC) [13].

The analysis carried out on the by-product recycling chain was fundamental to outline the sample flow chart (inventory analysis) and to evaluate the EE and EC performances (see paragraph 2).

The functional unit (f.u.) was 1 m^3 of mixture. The system boundaries for data input were also defined. Direct and generic data - subsequent to 2017 - and referring to Italy were used. Direct data were set out with enterprises involved in the research project or through Environmental Product Declaration; generic data were obtained through database consulting (Ecoinvent 3.0 and Agri-footprint 4.0). The cut-off rules have excluded those contributions of substances present in the samples that weighed less than 2% of the total weight. In this case, citric acid was excluded.

LCA based study was carried out with software SimaPro. The EE and EC calculation concerning plants (rice and corn) cultivation and harvesting were calculated by including land use, water consumption and emissions released by fertilisers and herbicides. The feedstock energy was not calculated. CO_2 absorbed by plants was also not included in the study. It can be assumed that if the CO_2 "credit" had been included in the calculation, the total value of the EC would have been lower than the determined value.

The by-products inventory analysis was carried out considering both the transport processes to the production stage and the methodological indications of open-loop recycling [27]. This means that the by-products included a share of EE and EC resulting from the cultivation and harvesting processes of the plants. Moreover, the drying activities of the corn cob, both in terms of energy (EE) and emission (EC), have been considered for the LCA calculation [28].

The Sarotto Group's manufacturing phase was characterized taking into account the machinery currently used and through foreseeing the implementation of new equipment.

3.3 Results and discussion

The results achieved in the monitoring phase and through the LCA study were compared with a lightweight concrete block available on the market.

The comparison was carried out by analyzing two wall systems, both with non-loadbearing functions. One made with ECOFFI blocks, one made with cellular concrete based blocks (Ytong® Climagold and Ytong® Sismico). See Table 3.

The ECOFFI bulk density and thermal conductivity are comparable to cellular concrete based blocks, according to intermediate values between the two analyzed Ytong® blocks. Concerning the U-value comparison was calculated according to current legislation requirements [29]. Taking into account an opaque wall for the coldest climate zone “F" it follows that the U-value must be less than 0,24 W/m^{2}K. The U-value obtained with the ECOFFI block is noteworthy (U = 0,22 W/m^{2}K) and a little higher than Ytong® Climagold cellular concrete. The calculation method did not include the addition of an insulating material layer to the wall as well as a plaster as finish work.

Through the LCA analysis was calculated a value of EE of 1279,8 MJ/m^3 and EC of 191,7 kgCO$_{2eq}$/m^3.

For the mentioned indicator the comparison with the cellular concrete blocks was determined by the following unit: 1 m^2 of a wall made with ECOFFI blocks; 1 m^2 made with Ytong® blocks. The Ytong® blocks EE and EC values were obtained from a Politecnico di Milano research report [30].

Table 3. Comparison of materials [Author processing]

Symbol	**Parameter**	**Unit of measure**	**ECOFFI**	**YTONG Climagold - Sismico**
ρ	Bulk density	kg/m^3	540	300 - 575
λ	Thermal conductivity	W/mK	0,088	0,072 - 0,143
ρ	Thermal transmittance	W/m^{2}K	0,22	0,17 - 2,71
EE	Embodied Energy	MJ/m^2	511,8	348,72 - 601,54
EC	Embodied Carbon	kgCO$_2$/m^2	76,7	40,68 - 70,17

The results of the comparison reveal that the wall made by the ECOFFI blocks had less EE than the traditional wall similar EE than the Ytong® wall. In fact, despite the high density of the ECOFFI block, the EE value is intermediate compared to the two Ytong® blocks. Such a result can be explained by the use of natural cement (lower EE value than traditional cement) and by the addition of natural aggregates and vegetable fibers. While the EC value is a bit higher than the EC Ytong® values. As already mentioned for the ECOFFI EC calculation, the CO$_2$ absorbed (credit) by rice-straw and corn-cob during their growing was not considered. Any widening of the boundaries system could lead to a value reduction of EC that would make ECOFFI fully competitive with the Ytong® system.

Finally, it is necessary to point out that the end of life stage of the ECOFFI block has not yet been evaluated. Although the ECOFFI block is not completely biodegradable - like other cement-based products it may be recycled as road inert or for the construction of substrates [31] [32].

4 Conclusion

The analysis about the agricultural by-products, their quantities, the study of possible recycling scenarios and, finally, the experimentation carried out on samples, proved the possibilities to the cross-fertilization between sectors: architecture and agriculture. Particularly through experiments carried out on the ECOFFI samples, was possible enhancing "poor" agricultural residues.

The investigation on corn crops has highlighted a large annual availability of such by-products. Nevertheless, it is currently impossible to predict a supply chain that can collect, store and use the potential residues.

The proposal described concerning the two by-product recovery chains (rice straw and corn cob), if put into practice, would allow the development of an interesting industrial symbiosis project. Some investment would be needed for equipment, while industrial players are already operating on the market.

Finally, the LCA based study verified the eco-compatibility of the ECOFFI. Further analysis might make it suitable to the public procurement [33] targeting it to new environmentally-friendly opportunities.

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