The International Journal of Life Cycle Assessment (2023) 28:813–827
https://doi.org/10.1007/s11367-023-02152-2

BUILDING COMPONENTS AND BUILDINGS

Environmental assessment of a new building envelope material derived from urban agriculture wastes: the case of the tomato plants stems

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Received: 9 June 2022 / Accepted: 27 February 2023 / Published online: 30 March 2023

Abstract

Purpose Decarbonizing cities is one of today's biggest challenges. In this regard, particular attention has been paid on improving the environmental performance of buildings. In this framework, this work consists in assessing the environmental impact of an innovative building envelope component derived from urban agriculture (UA) wastes. In fact, rooftop UA seems to be a possible solution to the rising food demand due to increasing urban demographic growth. Consequently, rooftop UA wastes need to be treated in sustainable ways.

Methods This study aims to determine the carbon footprint and embodied energy of a new infill wall material, derived from UA wastes produced by a building rooftop greenhouse tomato crop, and evaluate the potential biogenic carbon that such by-product could fix temporally until its end of life. After an initial description of the manufacturing process of the new material, its carbon footprint and embodied energy have been calculated by means of the life cycle assessment (LCA) methodology according to the ISO 14044 and the ISO 14067 guidelines adapted to the analyzed context. In particular, the inventory analysis is based on data collected from the production of samples of the new material at the laboratory scale.

Results and discussion The results of the LCA indicate that, when the biogenic carbon fixed in the UA wastes is considered, a negative carbon footprint of − 0.2 kg CO_2 eq. per kg of material can be obtained. Hence, it can be assumed that from a life cycle perspective the material is able to fix carbon emissions instead of emitting them. Specifically, for the considered scenario, approximately 0.42 kg CO_2 eq./m^2 per year could be sequestered. However, the crop area required to produce enough waste to manufacture a unit of material is quite high. Therefore, future studies should focus on individuate solutions to reduce the density of the new component, and also different urban crops with higher waste production rates.

Conclusions The outcomes of the study put in evidence the potential of the new proposed infill wall component in fixing carbon emissions from UA, allowing to also compensate those relating to the production and transportation stages of the component life cycle. Moreover, producing by-products with UA wastes, hence temporally storing the carbon fixed by crops, may contribute to reduce the carbon cycles speed conversely to traditional waste management solutions, other than lower new raw materials depletion.

Keywords Innovative building envelope components · Infill wall material · Urban agriculture wastes · Biogenic carbon · Carbon footprint · LCA · Embodied energy

1 Introduction

Decarbonized urban environments are crucial items for a future that is environmentally sustainable, energy resilient and economically viable within the current and future climate change scenarios (UNFCCC 2021; Finkbeiner and Bach 2021). It is, indeed, well evident how in the last few decades cities have been increasingly affected by different types of threats, i.e. natural shocks (e.g., heatwaves, floods), climate change and intensification in migratory flows (long-term stresses); the negative impacts of which they are quite often unable to cope (UCCRN 2018; Buggin et al. 2019). More recently, the pandemic (Covid19) and energy-economic crises (Ukraine-Russia conflict) have even more highlighted the need for a more sustainable and self-sufficient urban

Communicated by Vanessa Bach.

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metabolism, while still aimed at mitigating climate change (Ipsen et al. 2019; Salvia et al. 2021). Urban settlements, in fact, are subjected to a constant process of urbanization linked to demographic variations (Massacritica 2015; UN 2019) that requires an uninterrupted supply of food, materials and energy, releasing just as many atmospheric pollutants (IEA 2019a; EEA 2020). In 2018, 55.3% of the world population was estimated residing in urbanized areas, compared to 30% in 1950, and it is predicted that by 2050 the percentage will rise to 66% (Massacritica 2015; UN 2019; Santamouris 2020).

All these aspects implicate a constant change of cities, affecting the performance of public and private buildings within them. In fact, according to recently released bulletins on energy consumption and related pollutant emissions, the building sector accounts for 25–40% of the overall energy use at global, European and Italian levels, corresponding to shares of energy-related CO_2 emissions comprised between 17.5% and 39% (Tsemekidi et al. 2020; ENEA 2020a; IEA 2019b).

In this regard, recent initiatives, regulations and economic bonuses, concerning urban sustainability issued at global, European and national levels, place particular attention on improving the energy and environmental performance of buildings in order to enhance urban resilience to climate change. On this subject, the UN Sustainable Development Goals—SDGs (specifically, "Goal 11—Make cities and human settlements inclusive, safe, resilient and sustainable", "Goal 12—Responsible consumption and production" and "Goal 13—Climate action") (UN 2015a) and 2030 Agenda for Sustainable Development (UN 2015b), the EU climate-energy frameworks, long-term strategies (European Commission 2014; European Commission 2018) and Recovery Plan Next-Generation EU (European Commission 2020) are just a few to be cited. Along with those expressly intended for buildings, i.e. the EU Ecolabel for buildings products (Peri and Rizzo 2012; Capitano et al. 2014; EU 2017; Cirrincione et al. 2020a) and the Energy performance of Building Directives—EPBD (European Union 2010; European Union 2012); the latter, in particular, introduce the concept of nearly zero-energy (NZE) buildings according to which the energy required to meet the needs of buildings should be extensively covered by renewable sources produced on site or nearby. That is why, promote and assess the feasibility of initiatives aimed at improving resilience (Berardi and Jafarpur 2020; Cirrincione et al. 2021) and foster the sustainability of the built environment (Bisegna et al. 2019; Manfren et al. 2021a), on smaller and bigger scales (Guerrieri et al. 2019), represent some of the major commitments/challenges of the last decades for scientific communities in order to increase decarbonization to mitigate and combat climate change (Nastasi 2022).

In this framework, the concepts of climate and carbon neutrality have lately been increasingly applied to both new and old buildings since they constitute a predominant component of urban contexts, although such theme has been investigated mainly by considering active solutions (e.g. use of renewable energy sources) aimed at accomplishing energy efficiency (Cirrincione et al. 2019; Li et al. 2021; Nutkiewicz et al. 2021) and economic savings (Manfren et al. 2022, 2021b), while also enhancing citizens comfort, health and wellbeing (ENEA 2020b; Cirrincione e al. 2020b; Kousis and Pisello 2020). Therefore, some aspects need to be further investigated in order to push forward urban building decarbonization by also including passive measures in the picture (Cirrincione et al. 2020c; Napoli et al. 2022). This opens up an opportunity to rethink the passive energy performance of buildings. Specifically, an accurate design of the external envelopes (which constitute a relevant part of a building), aimed at reducing their environmental impact, should properly take into account the construction characteristics, the climatic context in which buildings are located and the possibility of employing local waste for the production of innovative materials, so as to also reduce the environmental impacts related to waste management and its transportation (Jeswani et al. 2013; Cirrincione et al. 2022). Consequently, the environmental, energy and economic benefits and limitations of synthetic and renewable/natural materials used for the envelope have been extensively analyzed in the literature focusing the attention to the use phase of buildings (Ferrante et al. 2016; Rodrigues et al. 2017; Capitano et al. 2017; Capitano et al. 2022).

However, in addition to the operational one the overall energy related to a building also includes its embodied one, which is the energy sequestered by all the materials composing a building throughout its entire life cycle from production to disposal (Pacheco-Torgal et al. 2012; Pacheco-Torgal 2014; Kiss et al. 2022), and that therefore should not be overlooked. As it has already been demonstrated, indeed, one of the most influential components in the environmental performance of buildings (both in the construction and use phases) is represented by the envelope, which could reach 30 to 50% of the embodied energy depending on the used material (Sierra-Pérez et al. 2016a, 2016b).

To achieve carbon neutrality, therefore, appropriate decarbonization strategies are needed. More in detail, according to some of the most established decarbonization approaches (Andrews 2014; UNFCCC 2021), the path towards carbon neutrality entails different actions ranging from avoiding carbon intensive activities, to reducing the use of traditional (fossil-fuel-based) raw materials and energy sources and/or replacing them with natural, renewable or waste-derived alternatives, to balancing and compensating the unavoidable emissions (Fabbri et al. 2020; Ferrante et al. 2015; La Gennusa et al. 2017; Lu et al. 2021).

At the same time, the demographic growth experienced in recent decades has led to a growing food demand as well, which will tend to furtherly increase in the near future. As a consequence, along with increased attention to environmental issues related to climate change (local production and reduced transportation), the use of urban agriculture (UA) has intensified, gradually beginning to be seen as a viable alternative to rural agriculture not only from a purely feeding (food-self-sufficiency) point of view (Tomlinson 2011; Rufí-Salís et al. 2020; Sanyé-Mengual et al. 2015c), but also thanks to its attitude in reducing and mitigating the negative impacts exerted on natural and urban areas (Zezza and Tasciotti 2010) and its potentiality in providing relevant social and economic benefits (Orsini et al. 2013; Specht et al. 2013; Sanyé-Mengual et al. 2015a). On the other hand, the increased UA activity reflects in a growth of agricultural waste production and that could represent a criticality in urban environments. Vegetal wastes, in fact, commonly have three possible disposal scenarios, i.e. landfilling, composting and incineration, all of which do not allow crops to act as a carbon capture and storage system (Peri et al. 2022; Rizzo et al. 2023). Conversely, such disposal scenarios return the sequestered carbon to the atmosphere in a brief period (less than 1–2 years) in terms of CO, CO_2 or CH_4 emissions (La Gennusa et al. 2016). Thus, these emissions can be considered part of a fast carbon cycle. According to the current concern regarding climate change, there is great interest in preventing these fast carbon emissions. Producing new building materials with valueless agricultural wastes, which can be instead considered valuable feedstocks, would avoid the conventional disposal scenarios and create stable materials with long lifespans (20 years or more) that could store CO_2 emissions sequestered by crops, transforming them into biogenic carbon. Therefore, UA could conceptually provide sustainable food to cities as well as low-carbon raw materials to produce new and sustainable by-products, resulting in the reduction of the carbon footprint related to crops, buildings and by-products derived from UA waste (Sanyé-Mengual et al. 2015b). Hence, based on these assumptions and also from a circular economy standpoint, a good way to manage UA waste, and thus transform it from a criticality to a valuable opportunity, is to reuse it as an alternative natural raw material for the production of innovative low-impact building envelope components in the vicinity of the place where they are intended to be used. According to such local scale production scenario, indeed, the carbon emissions fixed by UA waste-based envelope materials would likely be higher than the pollutant emissions generated during the production and transportation stages of the materials. In addition, the depletion of other raw materials would be avoided. Nevertheless, to the best of our knowledge, a lack of an overall environmental assessments of such local scale low-impact scenario has emerged (Sierra-Pérez et al. 2016a).

In the aim of giving a contribution to cover this research gap, this work presents the environmental assessment of the manufacturing of an infill wall component (envelope material) produced employing tomato plant stems (UA waste) to be used in the construction and/or restoration of buildings sited in the proximity of the production facility (in the Barcelona area, Spain). This type of UA waste has been selected based on the facts that tomatoes are a widespread crop and their plants wastes present several composting difficulties due to their high salinity and lignin content (Dunlop et al. 2015; Llorach-Massana et al. 2017), so from a life-cycle perspective it is highly encouraged to find alternative uses for them as a by-products. Specifically, the LCA methodology has been applied to determine the carbon footprint and embodied energy, in terms of carbon equivalent emissions (CO_2 eq.), embedded as biogenic carbon within the envelope material under study. Finally, the environmental impact of the new proposed envelope material has been compared to that of the most commonly used infill wall components on the market.

2 Materials and methods

As previously mentioned, the new innovative composite biomaterial is based on plant fibers derived from the pruning shoots of tomato plants. More specifically, this new material is intended to be used as a building envelope (i.e. exterior masonry) infill element as a sustainable alternative to the most common materials currently used for this purpose in the climatic and construction context analyzed, namely hollow bricks, tuff blocks and light concrete blocks.

This section describes in detail the feedstocks used to produce the new infill wall (envelope) material, the production procedure of such material and the approaches utilized to perform the environmental assessment of the new material in order to also determine its carbon footprint and embodied energy according to the Life Cycle Assessment (LCA) methodology, in reference to the analyzed context. The well-known LCA approach has, indeed, proven to be an effective instrument to support actions aimed at the environmental improvement of the building sector (Allacker et al. 2019; Mirzaie et al. 2020; Fnais et al. 2022).

Specifically, the main objectives of the environmental assessment of the new material are: (i) to determine the fixed biogenic carbon; (ii) to perform a LCA of the new UA waste-based material; (iii) to compare the carbon footprint and embodied energy of the new UA waste-based material with those of other traditional infill wall components; (iv) to provide limits and recommendations for the production of more sustainable infill wall materials produced with tomato waste plants.

2.1 Feedstocks used to build the new envelope material

To build the new envelope material, tomato plant (*Solanum lycopersicum arawak* variety) stems have been employed; such vegetal material came from a UA crop planted on the

Integrated Rooftop Greenhouse Laboratory (i-RTG-Lab) situated on the top of the ICTA-ICP building (Fig. 1) located in the Universitat Autònoma de Barcelona campus (Bellaterra, Spain), part of an experimental vertical farming installment (Pons et al. 2015). Rooftop greenhouses are a reality that has become increasingly popular in recent years, thanks to the benefits they provide for.

In this study, two samples elaborated with different proportions of tomato plant wastes and other materials (sand, water and hydrated lime) have been proposed and analyzed. The sample properties and production properties will be described in depth in Sect. 2.2.4.

2.1.1 Carbon content of UA tomato plants waste and carbon sequesterable by the new material

The carbon (C) content of the tomato plant wastes used for the study has been determined through elemental analysis using a LECO© analyzer (LECO 2021). Then, Eq. 1 was used to estimate the potential CO_2 equivalent (CO_2 eq.) emissions that the waste of the i-RTG could sequester ($C_{sequestered}$) on annual basis.

$$C_{sequestered} = \frac{DW_{prod.}}{A_{i-RTG}} \cdot C_{\%} + O_{2eq.} = \frac{\text{kg}CO_2eq.}{m^2 \cdot year} \tag{1}$$

where $DW_{prod.}$ is the annual i-RTG dry waste production obtained by weighing the waste of tomato plants stems and leaves at the end of a crop cycle, A_{i-RTG} is the i-RTG crop area equal to 84.3 m^2, $C_{\%}$ is the percentage of carbon content in dry waste per unit of mass measured through elemental analysis of the plants stems and $O_{2eq.}$ is the equivalent mass (kg) of oxygen from the CO_2 emissions fixed as C within the dry waste.

Referring to the analyzed case, the i-RTG, with a crop area of 84.3 m^2, produces 27.4 kg of dry waste tomato stem annually, equivalent to 0.33 kg/(m^2 year), while the C content in waste stems correspond to 35.7% of the total dry mass. Consequently, according to Eq. 1, the i-RTG-Lab tomato crop has the potential to sequester 0.42 kg CO_2 eq/(m^2 year), which could be fixed by using such waste to produce the new building envelope material, i.e. UA by-product, as proposed in this study.

Based on these considerations, two possible scenarios can occur. On the one hand, if the sequestered emissions are higher than those relating to the production and transportation of the new UA waste-based envelope material, it could be assumed that carbon emissions from production and transportation of the new material could be compensated by the biogenic carbon stored into tomato stems and leaves. On the other hand, if the opposite circumstance occurs (i.e. if the sequestered emissions are lower than those relating to the production and transportation phases of the new material), the carbon footprint of the new UA waste-based component would still be lower compared to that attributable to traditional products since the depletion of other raw materials would be avoided.

2.2 Environmental assessment of the new material

In this section the authors describe the approach used to assess the comprehensive environmental impact of the new building material.

2.2.1 Goal and scope definition

In order to fully and thoroughly assess the environmental impact of the two samples (A and B) of the new material three main aspects were investigated. Precisely, other than performing a classic Life Cycle Assessment (LCA), it was decided to also estimate the carbon footprint and the embodied energy indicators (that are based on the LCA methodology as well), for a dual scope as better explained in the following. Specifically, the carbon footprint and embodied energy indicators were chosen mainly for the purpose of making a comparison between the new material and some other conventional (non-natural-based) most commonly

Fig. 1 ICT-ICP building (left), inside of the i-RTG-Lab (middle) and experimental tomato crop (right)

used infill wall materials on the market (i.e. hollow bricks, tuff blocks and light concrete blocks) in a rapid manner and based on two valid and recognized indicators. While, the LCA was applied to the two samples (A and B) of the new material to compare them with each other more thoroughly also in reference to other possible critical environmental issues not directly highlighted by the carbon footprint and embodied energy indicators.

The carbon footprint (kgCO_2 eq.) is defined as "a measure of the total amount of carbon dioxide (CO_2) and methane (CH_4) emissions of a defined population, system or activity, considering all relevant sources, sinks and storage within the spatial and temporal boundary of the population, system or activity of interest…and it is calculated in terms of carbon dioxide equivalent (CO_2 eq.) emissions" (IPCC 2014). To proceed with the carbon footprint calculation, the GHG protocol calculation method (ISO 2018) was applied to determine fossil CO_2, biogenic CO_2 and CO_2 uptake.

While, the embodied energy—EE (MJ) is given by the sum of all of the energy required to produce any goods or services, considered as if that energy was incorporated in the product itself (Goedkoop et al. 2009).

As for the LCA (ISO 2021), according to the Environmental Product Declaration (EPD) for construction products (CEN 2021), the following impact categories have been considered:

- Climate change—GWP, not including biogenic carbon (kg CO_2 eq.);
- Ozone depletion—ODP (kg CFC 11 eq.);
- Acidification—AP (kg SO_2 eq.);
- Eutrophication aquatic freshwater—EP-freshwater (kg P eq.);
- Eutrophication aquatic marine—EP-marine (kg N eq.);
- Photochemical ozone formation—POCP (kg NMVOC eq.);
- Water use—WDP (m^3);
- Depletion of abiotic resources—minerals and metals—ADP-minerals&metals (kg Sb eq.);
- Depletion of abiotic resources—fossil fuels—ADP-fossil (kg oil eq.);

To carry out the above analyses, i.e. EE estimation and LCA application, the Recipe midpoint (H) was selected as calculation method (Goedkoop et al. 2009; ReCiPe 2016; Huijbregts et al. 2017; Lamnatou et al. 2018); whilst SimaPro© software (https://simapro.com) in combination with the Ecoinvent database (https://ecoinvent.org) was used as applicative tool.

The choice to use the ReCiPe method stems from the fact that, although there might be more up-to-date (and more complicated) procedures, this still represents an effective and currently recognized (considered useful) method to convert life cycle inventories to a limited number of life cycle impact scores, as evidenced by recent studies that refer to it in the field of building construction (Batista dos Santos et al. 2022a, b; Shi et al. 2022; Goh et al. 2022).

2.2.2 Functional unit

Similar to previous LCA studies concerning other building materials (Pargana et al. 2014; Sierra-Pérez et al. 2016a), and considering that the new proposed material should ensure thermal insulation characteristics similar to other traditional infill wall components, the selected functional unit (FU) for the performed assessment has been defined as the mass (kg) of material required to provide a fixed thermal resistance R (m^2 K/W) for a given surface A (m^2), as reported in Eq. 2.

$$FU = R\lambda\rho A \tag{2}$$

where λ is the thermal conductivity (W/m K) and ρ is the density (kg/m^3) of the analyzed samples. For the purpose of this work it was decided to set values of 1 m^2 K/W and 1 m^2 for R and A, respectively.

2.2.3 Production process description and system boundaries

Figure 2 describes the stages (raw materials, transportation and production) involved in the creation of the proposed infill wall material. This process is similar to that used by S. Benfratello et al. (2013) to produce a hemp-lime bio-composite insulation material. At the end of the tomato cropping period, plants are manually collected and placed next to the greenhouse where they are naturally dried. Once the plants are dry, their stems can be easily separated from the leaves. Then, dry wastes are transported to the production plant where they are chopped to obtain fibers of 4 mm in length and later mixed with water, sand and hydrated lime. The resulting mixture is placed in a mold for 5 days, after which the mix is demolded and naturally dried. Once the mixture is dry, the infill wall material is ready for transportation to the installation point.

As Fig. 2 shows, the system boundaries include the UA waste raw material obtained (dry tomato plant stems), the transportation of such material to the production plant and the production of the infill wall component. The transportation of the finished product to the utilization point is not included in the system boundaries as it is not a mandatory requirement according to the EPD for construction products (CEN 2021). Moreover, since the object of this analysis is associated to the new material using the wastes produced by an already existent UA crop, the tomato production phase has not been included in the system boundaries as well. Nevertheless, it should be considered that the environmental impacts of tomato production may be also reduced because stem waste management would be avoided.

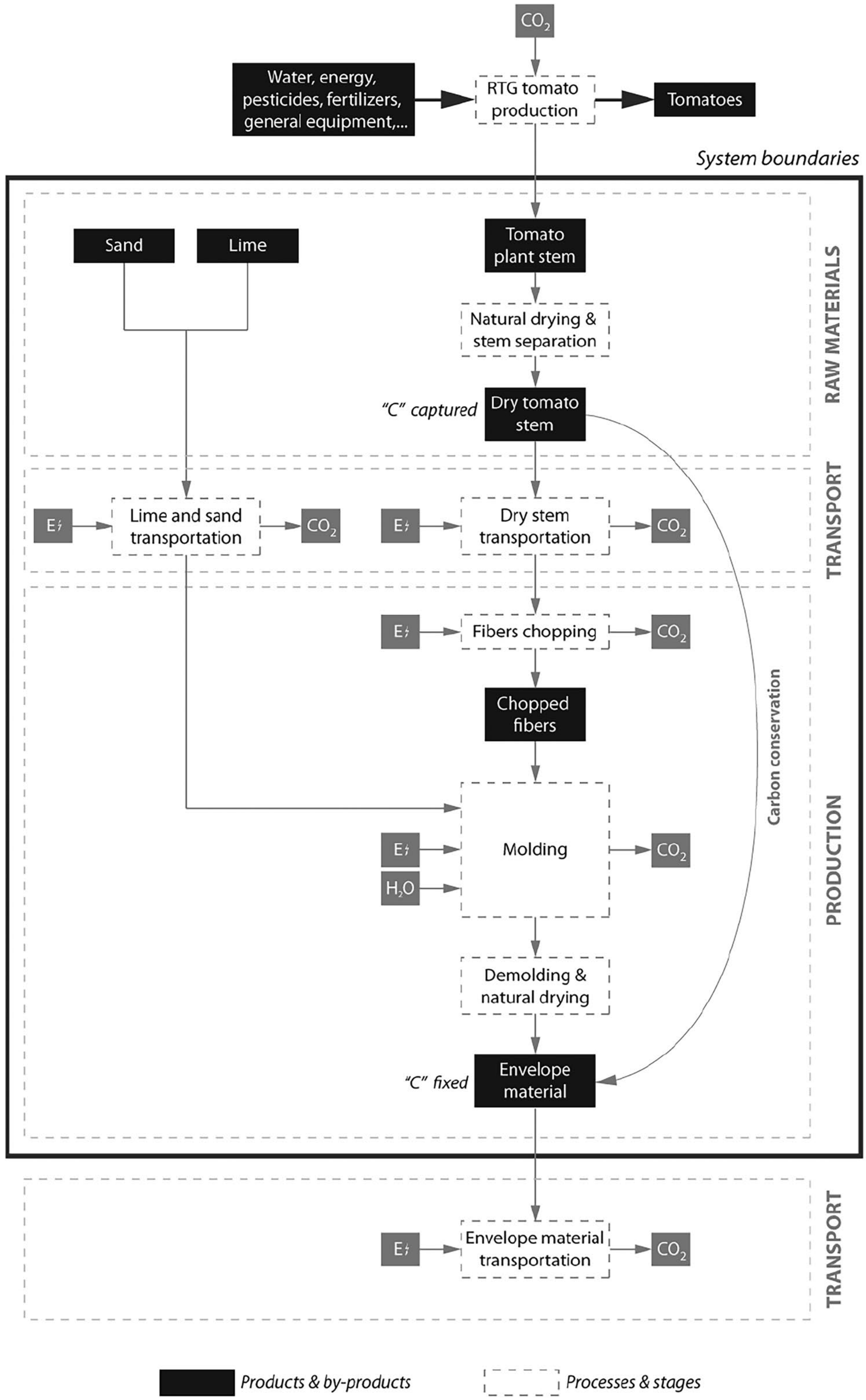

Fig. 2 Production process of the new envelope material and system boundaries selected for the LCA

2.2.4 Inventory assessment and assumptions

Two samples, A and B, have been produced (Fig. 3) and analyzed in this study according to the production process described in Fig. 2 and based on the proportions of a previous study on a hemp-lime bio-composite building material (Benfratello et al. 2013). For each sample different materials proportions were used (Table 1), in order to obtain samples

Fig. 3 Tomato plant stems (left) used for the production (middle) of the new infill wall material (right)

characterized by different properties and densities and, consequently, the total mass to achieve the FU varied for each of them. That is, for the same fixed value of thermal resistance (as reported in Sect. 2.2.2), in sample A it was decided to enhance mechanical characteristics, while in sample B it was decided to enhance thermal characteristics. Therefore, FU of sample A is characterized by larger thickness and heavier weight than FU of sample B. To do this, the composition of the two samples was made to vary as shown in Table 1. Nevertheless, it should be stressed again that, since the new bio-composite material is intended to be used as a sustainable alternative to other most commonly used building envelope infill components (i.e. hollow bricks, tuff blocks and light concrete blocks), both samples are able to meet the minimum characteristics required for such a type of building element.

Regarding the production plant, it has been assumed that it could be sited either in northern or southern Barcelona, where different industrial areas can be found; hence, assuming an average distance of 25 km between i-RTG-Lab and the production plant. As for the transport means, Euro 6 lorries with a load capacity of between 3.5 and 7.5 tons have been considered.

Lime and sand could be provided from a local quarry located in Garraf, 35 km far from Barcelona, by means of Euro 6 lorries, as well, with a load capacity of between 7.5 and 16 tons.

Euro 6 trucks were considered because these represent the most prevalent heavy goods vehicles HGVs in the area, and it is assumed that they will not be replaced in the near future (TLT 2016).

The energy required to chop the fibers and to perform the molding process was estimated considering the power needed by the equipment used (kW) and the operation time (h) required to produce one unit of mass (kg) of infill wall material, referring to the Spanish energy mix (RED). These data were registered and collected for each analyzed sample, resulting in an energy consumption for kg of stems equal to 0.984 kWh and 0.165 kWh for chopping and molding processes, respectively.

Table 1 Sample properties for the selected FU

	Parameter	Unit	Sample A	Sample B
Composition	Stem fiber content	%	20%	30%
	Lime content	%	32%	28%
	Sand content (carbonate calcium)	%	32%	28%
	Water content	%	16%	14%
Properties	Weight to produce the FU	kg	75.7	42.8
	Density	kg/m^3	733.7	658.3
	Thermal conductivity	W/(m K)	0.103	0.065

2.2.5 Carbon removal from the atmosphere

As previously reported, to proceed with the carbon footprint calculation, the GHG protocol calculation method (ISO 2018) was applied to determine fossil CO_2, biogenic CO_2 and CO_2 uptake. In particular, to simplify the calculation of the amount of CO_2 that is removed from the atmosphere when producing the new infill wall material, the following breakdown was adopted (Eq. 3).

$$C_{removal} = C_{rawmaterials} + C_{transportation} + C_{production} - C_{sequestered} \quad (3)$$

where $C_{raw\ materials}$, $C_{transportation}$ and $C_{production}$ represent the CO_2 emissions related to raw materials, transportation and production, respectively and have been extracted from SimaPro© software (https://simapro.com) by using the Recipe method (ReCiPe 2016); while, $C_{sequestered}$ is the amount of CO_2 sequestered by tomato plants, estimated as previously described in Sect. 2.1.1. In this study, it was assumed that carbon captured by plant remains stored in the new material, as is the case with other bio-composite lime-based materials such as concrete made with hemp (Ip and Miller 2012).

3 Results and discussion

In this section the results of the performed analyses will be reported and commented.

3.1 Environmental assessment of the new material and comparison between samples

Concerning the LCA, Table 2 shows a comparison between the outcomes of the analysis application to the two samples A and B for the considered impact categories.

Table 2 Comparison between sample A and sample B impact categories of LCA and impact reduction of sample B with respect to sample A

Impact category	Unit	Sample		Deviation of B from A
		A	B	
Climate change—GWP, not including biogenic carbon	kg CO_2 eq	9.9E+00	7.48E+00	−24%
Ozone depletion—ODP	kg CFC 11 eq	1.4E−06	1.09E−06	−22%
Acidification—AP	kg SO_2 eq	5.3E−02	3.99E−02	−25%
Eutrophication aquatic freshwater—EP-freshwater	kg P eq	1.8E−03	1.33E−03	−26%
Eutrophication aquatic marine—EP-marine	kg N eq	2.9E−02	2.25E−02	−22%
Photochemical ozone formation—POCP	kg NMVOC eq	3.2E−02	2.36E−02	−26%
Water use—WDP	m^3	8.3E−02	4.75E−02	−43%
Depletion of abiotic resources-minerals and metals—ADP-minerals&metals	kg Sb eq	2.7E−01	1.95E−01	−28%
Depletion of abiotic resources-fossil fuels—ADP-fossil	kg oil eq	3.0E+00	2.29E+00	−24%

As it can be noticed sample A is characterized by a higher environmental impact for all the considered categories. Specifically, on average sample A environmental impact is 26.3% higher than sample B. This can be ascribed to the fact that sample B has lower values of density and thermal conductivity most probably linked to the higher percentage of tomato stems compared to sample A; therefore, less raw materials (hydrated lime, sand and water) are required to produce a FU. Connected to this, the impact category with the largest difference (43% higher) is WD, which could, in fact, be explained by the fact that sample B uses 40% less water than sample A for all production stages. It should be also pointed out that, although a higher stem content within the material may be recommended, this could worsen the mechanical properties of the material.

Figure 4 shows sample A and sample B environmental impacts distributions for each of life cycle phase, i.e.

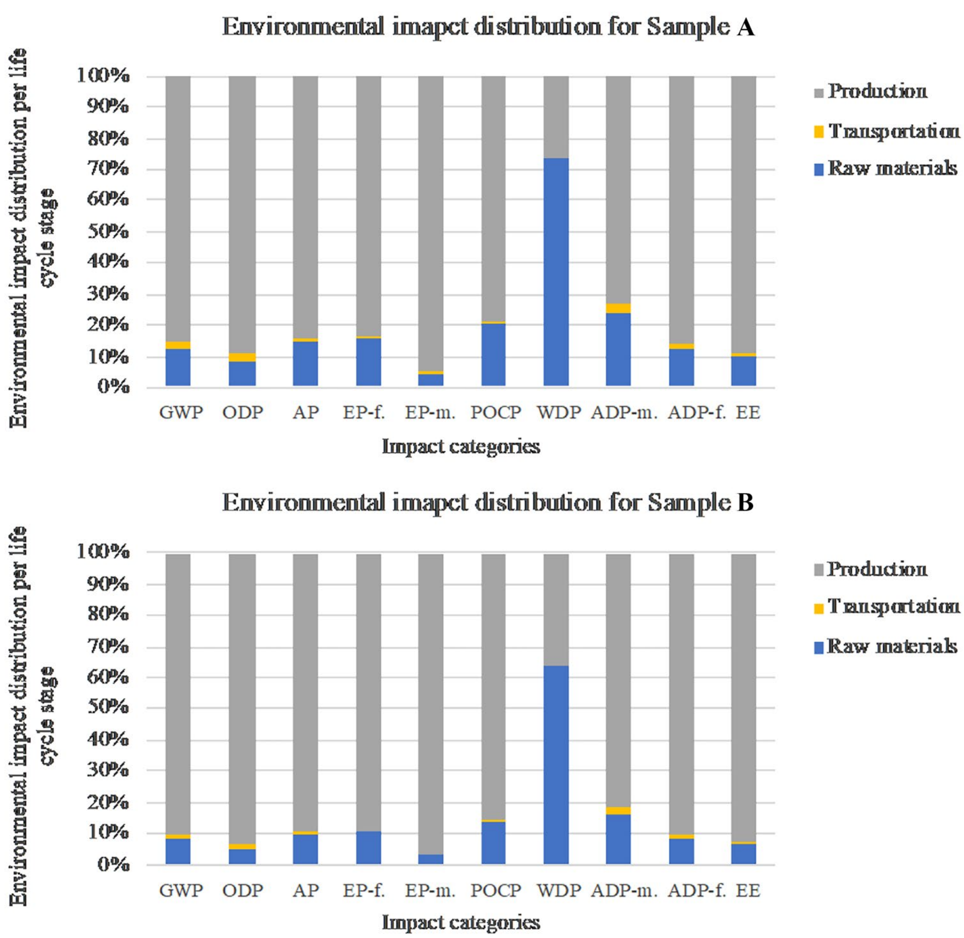

Fig. 4 Sample A and Sample B environmental impact distribution per life cycle stages (Climate change—GWP, not including biogenic carbon; ozone depletion—ODP; acidification—AP; eutrophication aquatic freshwater—EP-freshwater; eutrophication aquatic marine—EP-marine; photochemical ozone formation—POCP; water use—WDP; depletion of abiotic resources-minerals and metals—ADP-minerals&metals; depletion of abiotic resources-fossil fuels—ADP-fossil; embodied energy—EE)

production, transportation and raw materials. In this case, from the comparison of the two samples, no significant difference seems to occur.

As it can be observed, production is the main contributor to all of the impact categories except for WD, where the main contributor is raw materials, due the water required to produce the sample and to extract sand. From the performed analysis, it also resulted that the stem chopping process is responsible for a share of almost 90% of the production stage impact. It should be considered that the environmental impacts in the present study were calculated in reference to the manufacturing of samples at the laboratory scale. An industrialization of the process could reduce most of the environmental impacts associated to the production stage, although transportation-related impacts could increase.

Regarding the raw materials stage, this is responsible for less than 20% of the environmental impacts for all the categories, except for WD. In this case the largest impacts are caused by the supply of lime and sand needed to produce the samples, which are responsible of about 44% and 55% of the total environmental impact of raw materials stage, respectively. In particular, the impact associated to lime is probably caused by the calcination of stones extracted from mines at 1000 °C, while the impact related to sand could be ascribed to its grinding necessary to obtain sand powder. Water contributes to just 0.4% on the impact.

As for the transportation of raw materials to the production plant, this has a lowest environmental impact on all categories, i.e. less than 1%. The use of local materials seems to notably reduce the environmental impacts from the transportation phase in comparison with other studies for which this stage represents more than the 30% of the carbon footprint and embodied energy (Sierra-Pérez et al. 2016a). This confirms the appropriateness of the proposed strategy, i.e. using urban (rather than rural) agricultural wastes for innovative building envelope materials in the near area where they are to be used.

Regarding the Embodied Energy (EE) indicator the obtained results (which are also included in the following f Fig. 4) are equal to 2.0E + 02 MJ and 1.55E + 02 MJ for sample A and sample B, respectively, with an impact reduction of sample B with respect to sample A of − 22%.

As for the carbon footprint, the results for the two analyzed samples are reported in Table 3.

As it could have been expected, sample B is the one characterized by lower carbon footprint not including biogenic carbon. In fact, sample B, other than being characterized by a better thermal conductivity, is also the one requiring less material to produce a FU and causing lower environmental impacts.

In Table 3 net carbon footprint refers to the difference between the emissions generated during the raw materials, transportation and production stages minus the C emissions fixed by the tomato stems used to produce the samples. As it can be seen, for both samples the net carbon footprint is negative, meaning that the biogenic carbon fixed within the material is higher than the emissions resulting from the production of the same material, from a life cycle perspective. On average, fixed biogenic carbon reduces the carbon footprint by 212%. Such carbon fixed within the infill wall materials will finally come back to the atmosphere at the end-of-life of the material; however, the speed of the carbon cycles, in comparison with conventional waste management solutions (i.e. incineration and/or composting), has been significantly reduced. It should also be reminded that emissions from end-of-life are not accounted as they are out of the defined system boundaries.

3.2 Comparison with other infill wall materials of the building envelope

To elaborate further on the analysis, it was then decided to compare the new material with some other conventional (non-natural-based) most commonly used infill wall components on the market, i.e. hollow bricks, tuff blocks and light concrete blocks.

From the data reported in Table 4 it can be seen how both sample A and sample B present lower values of the thermal conductivity and density in comparison to the other conventional materials, indicating that an elevated mass is required to produce a FU; consequently, the building structure might need to be reinforced for the installation of the new material, which would increase the overall environmental impact of the building.

Table 3 Carbon footprint of the analyzed samples according to the defined FU

	Raw materials, transportation and production				Tomato plant waste biogenic carbon content	Ratio CO_2 in waste/emitted for transformation	Net carbon footprint*
	Fossil CO_2 eq	Biogenic CO_2 eq	CO_2 uptake	Total			
	$kgCO_2$ eq	$kgCO_2$ eq	$kgCO_2$ eq	$kgCO_2$ eq	$kgCO_2$ eq	%	$kgCO_2$ eq
Sample A	9.9	0.2	0.2	9.9	19.8	2.0	− 9.9
Sample B	7.5	0.2	− 0.2	7.5	16.8	2.7	− 9.3

*Emissions from raw materials, transportation and production stages minus C emissions fixed within the tomato stems

Table 4 Comparison between sample A, sample B and other commonly used infill wall materials (Hammond and Jones 2006; Hammond and Jones 2008; UNI 2014)

	Thermal conductivity	Density	FU (weight)	Life cycle perspective	
				Carbon footprint	Embodied energy
	W/(K m)	kg/m^3	kg	kgCO$_2$ eq	MJ
Tomato stem (Sample A)*	0.103	733.7	75.7	9.9	202.9
Tomato stem (Sample A)**	0.103	733.7	75.7	−9.9	202.9
Tomato stem (Sample B)*	0.065	658.3	42.8	7.5	155.5
Tomato stem (Sample B)**	0.065	658.3	42.8	−9.3	155.5
Hollow bricks	0.337	1000	337.1	74.2	1011.2
Tuff blocks	0.550	1600	880	15	264
Light concrete blocks	0.500	1400	700	231	2450

*Not including biogenic carbon

**Including biogenic carbon

Anyway, despite such possible limitation (that should be further explored in order to be verified), based on the obtained carbon footprint and embodied energy values, the new material seems to be characterized by a better environmental performance from a life cycle perspective compared to the other materials. This is probably due to the fact that the lower impacts associated to the raw materials transportation may compensate for the higher impact related to the amount of raw materials required to produce a FU.

It must also be underlined that a difference can be observed depending on whether the biogenic carbon is considered or not. In fact, if biogenic carbon is taken into account, despite embodied energy value remaining unchanged, the actual environmental impact in terms of CO_2 eq. emissions would be lower. Therefore, if biogenic carbon is included when computing the CO_2 emissions, embodied energy should not be used as the main indicator for decision-making purposes when selecting more environmentally friendly materials.

3.3 Potential production of the new material

Aside from the amount of carbon sequesterable by the new material, it is also important to determine the quantity of infill wall material that could be manufactured per area of crop. In fact, this information could be essential to estimate if in the future UA could supply enough waste to produce the infill wall materials that a city may demand for new and/or to be restored buildings.

The potential annual production of the i-RTG-Lab resulted being 1.6 and 1.1 kg/m^2 year of infill wall material for samples A and sample B, respectively. The higher value obtained for sample A is ascribable to the fact that the tomato fiber content in this case is lower (20%, see Table 1) than that of sample B (30%, see Table 1). Consequently, the crop surface required to produce a FU (i.e. for 1 m^2 of infill wall material) is equal to 46.6 m^2 and 39.5 m^2 for samples A and B, respectively. These values were, indeed, calculated by dividing the mass of infill wall material needed to produce the FU (Table 1) by the above mentioned potential annual production. These results show that about half of the annual wastes produced by the i-RTG-Lab surface (total area of 84.3 m^2) are required to produce 1 m^2 of material.

Approximately 215 m^2 or 253 m^2 of infill wall surface area could be produced per hectare of a crop for sample A or sample B, respectively. Meaning that, for example, the infill wall material needed for the for external envelope of a 4-floor building (20 m wide, 20 m long and 15 m high) with an external surface of 1600 m^2 (without discounting empty surfaces for windows) would require an annual waste production of 7.5 hectares or 6.3 hectares of tomato crop for sample A or sample B, respectively. Therefore, the dimensions of UA may limit the production of infill wall materials, such as those proposed in the present research. Consequently, it may be necessary to retrieve waste stems from non-UA crops, going from peri-urban to rural contexts. Such circumstance, however, as previously mentioned would cause an increase of the transportation distances, hence, of the environmental impact of the new material.

4 Conclusions

The present work started from considerations regarding a possible and innovative solution to contribute to the decarbonization of urban environments. In fact, so far in order to tackle climate change the attention of researchers has been mainly paid to the attempt of limiting the energy consumption (and pollutant emissions) of buildings guaranteeing the required performances to the outdoor and indoor air; while, more recently the threats related to the pandemic and energy-economic crises have called for a more conscious design of strategies/solutions, aimed at a more sustainable and self-sufficient urban metabolism. Therefore, although the energy, environmental and health concerns remain on the table, the issues related to the economic and safety aspects, in terms of self-support based on local resources, must nowadays even more properly be addressed. In light of this, the main objective of the work has been that of assessing the environmental impact, from a life cycle carbon neutrality perspective, of an innovative building envelope component derived from local UA wastes to be used in the proximity of the production site. The innovative aspect lies in the possibility of addressing two problems simultaneously through a single solution, i.e. reduce urban wastes and use locally produced and more sustainable building materials.

The results of the assessment performed on the new proposed UA waste-based material put in evidence the significant potential of such a type of infill wall component in fixing carbon emissions from UA crops, allowing to also compensate those relating to the production and transportation stages of the new material life cycle. In particular, the higher the employed percentage of tomato plant stem is the lower the carbon footprint is, due to the biogenic carbon content. On the other hand, given the high density of the new infill wall component, an equally high amount of waste material is required for the production of the component. Therefore, different urban crops with higher waste production rates (e.g. pepper) are actually under consideration for further possible study.

Of course, it should be here underlined that this is a first investigation on this subject on which improvements can be made as a future research development. In fact, this study is meant as a preliminary analysis of the new bio-composite material as an innovative and sustainable solution to employ an already existent waste (produced by a greenhouse rooftop UA crop used for feeding purposes) that would result in an avoided impact relating, instead, to the supply and use of new raw materials. Anyway, the avoided impact deriving from new raw materials is certainly an interesting issue that deserves attention and that should thus be properly investigated in a future study. Indeed, this aspect is currently under the authors research considerations along with an assessment of the avoided impact deriving from waste management, product production and transportation, also in terms of stored biogenic carbon. Furthermore, analyses on durability and (later) fire resistance characteristics of the new material, that fall outside the scope of this study (aimed at investigating only the environmental impact), are being taken into possible consideration for subsequent studies to give a complete evaluation on the new bio-composite material.

In conclusion, the performed study highlighted how enhancing urban building carbon neutrality by making use of local waste based materials entails a series of short-term and long-term benefits, not only concerning the energy and environmental performance of buildings themselves and their surroundings, but that can also, in future perspective, affect an entire country by setting local economies in motion (e.g. new job opportunities), other than contributing to the strengthening of national security (reduced dependency on foreign supplies).

Acknowledgements This work was carried out within the Spanish research project "Agro-urban sustainability through rooftop greenhouses. Eco-innovation on residual flows of energy, water and CO_2 for food production" (MINECO: CTM2013-17-47067-C2-1-R) and the research project "SUSTAIN/ABLE—SimultaneoUs STructural And energetIc reNovAtion of BuiLdings through innovativE solutions" (20174RTL7W_003).

Author contribution All authors contributed to the study conceptualization, methodology, formal analysis and investigation, visualization and writing (original draft, review and editing). All authors read and approved the final manuscript.

Funding Open access funding provided by Università degli Studi di Palermo within the CRUI-CARE Agreement. The PRIN (Programmi di Ricerca Scientifica di Rilevante Interesse Nazionale) of the Italian Ministry of Education, University and Research.

Data availability Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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