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Identifying potential applications for residual biomass from urban agriculture through eco-ideation: Tomato stems from rooftop greenhouses

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ABSTRACT

Considering that urban agriculture (UA) is currently on the rise due to its multiple benefits in addition to environmental ones, it would also be necessary to foresee the flow of solid waste it generates, which if not properly managed or used, could become a new waste problem within the cities.

The main objective of this study is to take advantage of agro-urban solid waste (AUSW) from the perspective of Circular economy (CE) in order to, in addition to reducing the volume of AUSW within cities, to close the life cycle of UA allowing to continue with its multiple benefits.

Starting from a previous study on the classification and quantification of the AUSW generated in rooftop greenhouse (RTG) tomato crop, where it was determined that the waste with the greatest potential for use was tomato stems, in this study a methodology is proposed that part of the eco-design to take advantage of the tomato stems adding value (upcycling) through the approach of "do-it-yourself" (DIY) for local use.

First, the physical, chemical and mechanical characterization of the tomato stems was carried out and the materials with similar properties were identified using Ashby graphs.

Afterwards, a creative session was held where specialists in order to identify possible applications of the stems through group techniques for the generation of ideas and the evaluation of concepts.

Finally, tests were carried out with the material and a semi-quantitative evaluation of the resulting concepts was carried out using an eco-design metric. The resulting concepts were "Fences and trellises", "Packaging" and "Boards, panels and blocks".

In addition to the results obtained on the possible applications of the stems *in situ*, this study provides data on the characterization of the stems of tomato plants that could also be used for the use of biomass in other contexts and scales such as conventional agriculture.

1. Introduction

Rooftop greenhouses (RTG) are one of the urban agricultural systems involving the use of greenhouse methods with soilless cultivation systems and hydroponic techniques adapted for use on top of buildings (Sanyé-Mengual et al., 2015). This system has grown considerably in recent years in dense cities since it has allowed food production to be brought to cities to mitigate food shortages and reduce environmental impacts related to transport and packaging as well as other social benefits (Sanjuan-Delmás et al., 2018a, b). To make the RTG system more sustainable by improving its environmental performance and the efficiency of its resource use, several studies have been performed to take advantage of different flows such as energy (Nadal et al., 2017), water, CO_2 emissions (Pons et al., 2015; Sanjuan-Delmás et al., 2018a, b), N_2O emissions (Llorach-Massana et al., 2017b) and nutrients (Rufí-Salís

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et al., 2020). However, the residual biomass has not yet been fully investigated for this purpose through its *in situ* use. This organic fraction represents a new challenge since it is a new type of waste that would add to the rest of the waste produced within cities (Manríquez-Altamirano et al., 2020).

There is a great difference between the taxonomy of conventional agriculture system and urban agriculture (UA) system (Goldstein et al., 2016), therefore also in the solid waste (SW) flows. Considering that in addition to having a lower volume, agro-urban solid waste (AUSW) is generated within cities, which is a key point to consider its type of management.

Organic solid waste (OSW), biowaste or residual biomass within cities is usually managed by the municipality through a separate collection (Xevgenos et al., 2015). In this case, the residual biomass generated in RTG would be added to the pruning waste from parks and gardens (stems, branches and leaves) (Boldrin et al., 2011). This type of waste, unlike kitchen waste, takes longer to degrade because it contains a larger volume of lignocellulosic material, so it is usually preshredded for processing (Manríquez-Altamirano et al., 2020). Of the total waste selectively collected at the municipal level in Spain (2016), the biomass fraction from parks and gardens represented 7%, and 60% of this type of waste was destined for composting (MITECO and INE, 2016).

To improve the environment, the Circular Economy (CE) initiative was created to encourage changes in the way the entire economic system works, to convert from linear to circular flows (Korhonen et al., 2018). The CE seeks to maintain the value of products, materials and resources for as long as possible, minimizing the extraction of raw materials, the generation of waste and the emission of greenhouse gases related to the new production of products (Camarsa et al., 2017). In December 2015, the CE Action Plan for the EU (European Commission, 2015) was approved, which will help close the life cycles of products by increasing the rate of reuse and recycling of materials considered waste (Korhonen et al., 2018) through a “waste hierarchy” that includes a descending order of priority for waste management from a primarily environmental perspective. The first step is prevention, followed by preparation for reuse, recycling and recovery, and finally disposal (European Council, 2008).

Within recycling, upcycling is one of the CE strategies to increase the quality, functionality or aesthetic value of a material or product (Ahn and Lee, 2018; Sung, 2015). This term is a neologism that emerged in the 1990s (Bridgens et al., 2018) and has taken on greater relevance as a global concern for the use of local resources and the substitution of materials appears, minimizing environmental impact and reducing the generation of waste in cities. The “Do It Yourself (DIY)" approach is closely related to upcycling and waste management as it is based on self-production using shared knowledge of simple production processes, low cost and affordable manufacturing tools (Rognoli et al., 2015). This allows the use of material considered waste locally, which implies working with a material flow that may not be constant nor have a large volume, and its characteristics may vary, so it is necessary to use imagination and creativity to take advantage of these materials locally and generate useful products within a certain area with particular needs (Bridgens et al., 2018).

There are studies on the social perception of self-production through DIY that mention other benefits such as reducing dependence on commercial services in addition to helping people to be willing to learn new skills (Sung et al., 2014; Rognoli et al., 2015).

Also, there are studies where the DIY approach is applied to create eco-materials (Rognoli et al., 2015), for example, treating potato residues (Caliendo et al., 2020) or peanut shells to create bioplastics (Troiano et al., 2018).

The concept of eco-material was created in 1991 to refer to materials designed to minimize environmental impacts considering their complete life cycle (Halada et al., 2002; Wang et al., 2005).

Seeking environmental benefits within the CE, eco-design is a methodology to generate new product ideas complying with the requirements of environmental sustainability in the most efficient and appropriate way using different strategies of creativity, innovation and the participation of many different actors (López-Forniés et al., 2017). Eco-ideation is one of these strategies that is characterized by search, experimentation, participation, and the exchange of knowledge (Sierra-Pérez et al., 2016a; Demertzi et al., 2017) that can help generate concepts to create eco-friendly products or eco-materials that satisfy human needs taking into account the entire life cycle of the product (Karlsson and Luttropp, 2006). An example of the use of eco-ideation for the use of waste is the study by Sierra-Pérez et al. (2016b) on the cork industry, which shows that in addition to its use in wine stoppers, it can add value to the construction industry due to its physical characteristics.

Much of the studies on eco-materials focus on the use of vegetal material (Jústiz-Smith et al., 2008; Satyanarayana et al., 2009; Ahmed and Vijayarangan, 2008). Depending on the type of product to be produced, they may or may not be mixed with other materials to improve their resistance such as binders or products to improve resistance to moisture (Satyanarayana et al., 2009), insect and rodent repellants or treatments to increase their resistance to fire (Schiavoni et al., 2016). Most of these studies focus on the elaboration of bio-composites formed mainly of vegetable fibers as fillers in polymeric or biopolymeric matrices (Luo et al., 2017; Satyanarayana et al., 2009) that can serve as a substitute for plastic products, thermal insulators (La Gennusa et al., 2017; Kymäläinen and Sjöberg, 2008) or even as part of the mixture for the manufacture of concrete or bricks for the construction industry (Benfratello et al., 2013; Thieblesson et al., 2017). However, fewer studies use fibers from agricultural waste (biowaste) (Vega-Baudri et al., 2011; Franzoso et al., 2015; Evon et al., 2017; Nisticò et al., 2017; Palumbo et al., 2015; Schettini et al., 2013; Jústiz-Smith et al., 2008; Chua-Chil et al., 2012) unlike the studies that consider fiber crops like hemp, jute, flax, kenaf to make these eco-materials (Schiavoni et al., 2016). An important part of these studies is the characterization of the vegetal material to take advantage of its maximum potential, considering the best option for its use according to its properties (Azizi Mossello et al., 2010).

This research emerges from a previous study (Manríquez-Altamirano et al., 2020) on the classification and quantification of integrated RTG (i-RTG) solid waste to identify the potential use from a CE perspective. Those results showed that the organic fraction or residual biomass was the most critical type of i-RTG solid waste to manage within densely populated compact cities, and it had the greatest potential for local use according to its volume, generation timing and type of management. This is particularly true for the stems of tomato plants, which are generated only at the end of the crop and represent 33% of the total biomass. A future scenario for UA growth is also proposed, where an increase of 20% in the volume of OSW is expected, difficult to manage within cities, which could become a new problem to solve (Manríquez-Altamirano et al., 2020).

Base on the above, this research focuses on identifying applications for the use of tomato stems from the FertileCity (“Fertilecity”, 2018) project within the 2015 to 2018 period (three different crops) using an adaptation of the methodology presented by Sierra-Pérez et al. (2016b) (see Fig. 1). The crops were developed in the Urban Agriculture Laboratory (LAU1) of the ICTA-ICP building in Barcelona (Spain), with a total crop area of 84.34 m^2 and a production of 1269 kg/year avg (Manríquez-Altamirano et al., 2020). of edible tomatoes. It is a soilless crop system with 171 plants using

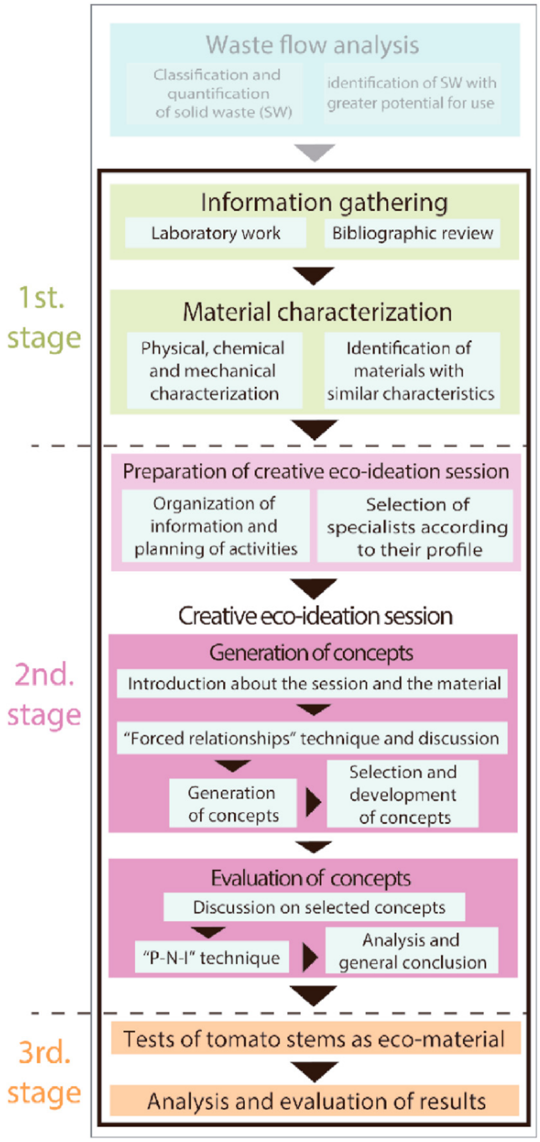


Fig. 1. Adapted from Sierra-Pérez et al. (2016b).

expanded perlite as a substrate to grow the Heart of ox ("Cor de bou") tomato (*Solanum lycopersicum*) variety Arawak (Sanjuan-Delmás et al., 2018a, b).

There are different ways of taking advantage of biomass, with composting being the most traditional and most widespread option (Burés et al., 2014; Ros, 2012) that could be used locally from a DIY perspective. However, the aim of this study is to find applications to add value to the residual biomass as a higher quality eco-material without losing the benefits of its development and use *in situ* promoted by the UA. Therefore, neither energy use nor chemical compounds (ingredients for the food or cosmetic industry) are considered.

The case study presented corresponds to the stems of the plant of one of the main products that is produced and consumed in Europe and in the world, the tomato.

Tomato production for 2018 in Europe was 16.7 million tons, 26.8% of the total agricultural production of vegetables. Of which, Spain produced 4.8 million tons, being the third country with the highest tomato production after Turkey and Italy in Europe (Eurostat, 2019). In Southeast Europe, 3.63% of the total protected area is grown with tomatoes, making it one of the most important greenhouse crops in the world (FAO, 2017). In Spain, the annual per capita consumption of tomatoes is 13.22 kg, 23.24% of the total consumption of fresh vegetables and the region of Catalonia, where Barcelona is located, which ranks first in annual per capita consumption of tomato in Spain with 15.78 kg (MAPA, 2018). In addition, it is the second most consumed vegetable after the white potato in Barcelona and its surroundings (Mercabarna, 2017).

Taking advantage of tomato stems from the CE perspective shows us a path to follow for upcycling through eco-ideation strategies to identify useful and viable applications at the local level within densely populated compact cities, such as many in Europe, using a DIY approach. This could help reduce this type of waste within cities and close the cycle of RTG OSW flow by improving its environmental life cycle performance.

2. Materials and methods

The materials and methods used to follow up the methodology are described below divided into their three stages (see Fig. 1).

2.1. First stage: Information gathering, material characterization and identification of materials with similar characteristics

For this research, data from five different tomato crops collected between February 2015 and July 2018 were used, from summer 2015 (S1), winter 2015 (W), summer (2016) S2, summer 2017 (S3) and summer 2018 (S4) (detailed information can be reviewed in Appendix A). A specific procedure is followed at the end of each crop (Manríquez-Altamirano et al., 2020). The stems are manually separated from the system and cut 20 cm from the base of the substrate bag. Subsequently, all the branches along with the leaves are separated from the main stems and then weighed and measured separately. The diameter of each stem is measured with an analog Vernier caliper at eight different heights, with the first starting from the cut point and then at 1 m, 2 m, 3 m, 4 m, 5 m, 6 m and finally 10 cm from the tip to the stems that exceed 6 m. The cross-section of the tomato stems usually have a semioval, amorphous shape, therefore, when measuring the diameter, the broadest part of this shape is considered. The stems are spread out in the soil to air dry for two months and are measured and weighed again. Samples equivalent to 68% of the total biomass were analyzed except for the 2018 samples, for which the total fresh biomass was analyzed.

Relevant information was collected on the stems from the previous crops of the FertileCity project generated by the Sustainability and Environmental Prevention research group ("Sostenipra", 2018). Subsequently, a review of the body of knowledge was performed on the scientific literature to search for data on the characterization of tomato stems through online catalogs (that is, Web of Science, Google Scholar and Scopus) using the term "tomato stems" as keywords, and the search was also refined using the words "characterization", "characteristics" and "properties", both separately and related. Subsequently, the citations referenced in the resulting articles were reviewed to find information that was relevant to this research.

A physical characterization was performed on the tomato stems of the S3 and S4 crops (fresh and dried naturally). For some of the tests, it was necessary to crush the dried tomato stems using a special crushing machine for compost (4 kW, 58 kg) (TECO Insaen, 2006).

The stem density is calculated by gravimetric displacement method using Archimedes' principle with a balance ($e = 1$ g $d = 0.1$ g) using dried tomato stem samples of known masses.

Soil degradation tests are performed on fresh stems using 10 samples consisting of 10 cm-long fresh stems averaging 15.89 g each. Each one was placed in containers with 90 g of soil (universal substrate) for eight months. The tests are reviewed to verify the total weight of each container and the weight, approximate diameter, and appearance of each stem sample at 15-day intervals for the first month and thereafter, each month. For soil degradation tests with dry stems, 10 samples of dry stems 10 cm long and weighing an average of 1.86 g are used. Each one was placed in containers with 104 g of soil (universal substrate) for five months. The tests are reviewed to verify the weight (balance: e = 0.1 g d = 0.01 g), diameter, and appearance of each stem sample at 15-day intervals for the first two months and each month thereafter. The outdoor degradation test is performed on three samples, A: 138 cm, B: 111 cm and C: 104 cm, of dry stems weighing 25 g each, which are placed on the roof for 12 months. They are weighed (balance: e = 1 g d = 0.1 g) and measured every month.

Water absorption capacity is evaluated based on the standard 24-h water absorption or balance test ASTM D570 (ASTM, 1985) with four samples of 1.35 g stems that were oven dried. Each sample was placed in a bottle with 60 ml of Elix® system-purified water. The moisture content was calculated by taking the difference between the weight of the fresh and dry samples based on Test D2216-05 (ASTM, 2005). Ash content is obtained by calculating the percentage difference between the initial weight of the dry stem samples and the weight of the ash after calcination in a muffle furnace, with a ramp of 5:30 h starting at room temperature (25 °C avg.) and increasing to 550 °C during 4 h with a drop in temperature due to thermal inertia. Four samples (a, b, c and d) measuring 35 g each (balance e = 1 mg d = 0.1 mg) of dried and crushed stems are used. After leaving the muffle furnace, the samples are placed in a Pyrex™ Borosilicate Glass Vacuum Desiccator during 24 h.

To determine the thermal conductivity (κ [W/m $\cdot$ K]) and heat capacity (Cp [J/m^3]) at room temperature, we use a Quickline-30 multifunctional thermal properties analyzer from Anter Corporation (Pittsburgh, PA, USA), which is based on the principle of transient heat line method. A surface sensor containing a heating coil was used directly on a sample of crushed tomato stems. This procedure was repeated at least three times (Haurie et al., 2014).

A chemical characterization was performed using composite samples of naturally dried stems from S3 and S4 crops, and data from the previous characterization of the S1, W and S2 crops were also used as references (Llorach-Massana et al., 2017a). Stems located in different parts of the crop are chosen to make the composite samples representative, in addition to using pieces from different stem heights. This characterization was performed by an external laboratory to obtain the cellulose, lignin and hemicellulose data by gravimetry and the basic elements of organic matter, namely N (obtained by thermal conductivity/C5110096), P, K, Ca, Mg, S, Fe, Zn, Cu, Mn, B, Na, Mo (obtained by ICP-OES spectrometry), C (obtained by thermal conductivity), Cr, Ni, Pb, Cd, Hg, Si, Al, Se, and As (obtained by ICP-OES spectrometry).

Mechanical characterization was performed using seven samples of dried stems with an average length of 13 cm from the S4 crop. This approach is based on tensile wich were completed at the Construction Materials Laboratory of the Barcelona Building Construction School (EPSEB-UPC) on a multiple electromechanical test press (Mecánica Científica, S.A.) through a built-in microprocessor and 300 kN load cell, were the break points of the samples and the following parameters were obtained: Young's modulus, elastic limit, tensile strength and elongation at break, and the values were averaged.

Once the characteristics of the material under study were achieved, other materials that present characteristics similar to those of tomato stems were identified through bibliographic information and the use of the graphical material selection method with the CES EduPack (GrantaDesign© 2018) software. Using the software, the "tomato stem" material was "created" by entering the values of its different physical, chemical, mechanical and thermal properties.

When the stem material appeared within the universe of materials, graphs were made that relate pairs of material properties. The area in which the "tomato stems" material was found was visually located with respect to other materials to identify to which "family of materials" it belonged to. The graphs were analyzed using tables to identify the materials with values closest to the tomato stems in each graph. According to the frequency of appearance in all the graphs, the five materials with the most similar characteristics to the tomato stems were selected. Later, the current applications of these materials that would serve as a reference for the participants in the eco-ideation session were identified.

2.2. Second stage: Creative eco-ideation session

This session was organized by two specialists in eco-design who acted as group coordinators, with one specialist in urban agriculture and another one in environmental and urban agriculture. Equipment was prepared to record video and audio of the entire session for later analysis. The interdisciplinary choice of participants sought diversity in the generation of concepts with a holistic approach. In addition to the area of knowledge in which they specialize, two different profiles can be defined that are required in the participants. On the one hand, there is the "creative" profile and on the other, the "technical" profile. A total of 10 specialists were invited to participate.

At the beginning of the creative session, the participants were made aware of the objectives and were shown information that was collected on tomato stems in a concise manner, on the materials with similar characteristics and their uses. Participants were divided into two interdisciplinary groups. Each group was assigned a coordinator who explained and directed the activities and indicated the duration of each activity.

The first part was the generation of application concepts using the "forced relationships" or "random stimulation" technique (Sierra-Pérez et al., 2016a, b). Each group was given 10 pairs of cards to flip randomly, some with the properties of the stems (identified with one color) and the others containing the market sector (identified with another color). The cards were flipped in such a way that when turning a pair of cards, the group would have to generate an application concept with the stems using the property indicated by the first card with the sector indicated by the second card. All the concepts were generated by "brainstorming". Subsequently, the second section began with the selection of the two concepts considered the most viable to develop, and based on these concepts, each group responded in a sheet on which the coordinator had posed the following key questions: "What is it? How can it be done? What difficulties does it have? and What differential factors does it have?" to develop each chosen concept in more detail. At the end of this activity, both teams got together.

Each team coordinator presented their two proposed concepts to the other group, which were discussed, detailed and synthesized into three resulting concepts. After that, using the "Evaluation Grid" technique, the three resulting concepts were presented as a column placed in a table, with four criteria as a title for the following columns with which each proposal would be evaluated. The criteria were innovation, technical feasibility, environment, and market impact, and were evaluated using the "positive, negative and interesting (P, N, I)" technique (Sierra-Pérez et al., 2016a, b). This technique consists of each participant using self-adhesive color notes to evaluate the ideas in a positive (green), negative (red) or interesting (yellow) way by writing a comment on their decision and placing them in the corresponding cell. To conclude the session, a brief analysis of the activities was performed, with the contribution of each participant regarding their specialty and knowledge and the general results of the qualitative evaluations.

2.3. Third stage: Testing, analysis and evaluation of results

Based on the concepts with the greatest potential to be developed from the creative session, tests were performed on the dried tomato stems of the S4 crop from the DIY perspective, by considering simple self-production processes.

To identify which of the resulting proposals was more feasible to develop as eco-material, the semi-quantitative evaluation of the concepts was achieved by adapting a metric developed by López-Forniés et al. (2017). It included the factors of Novelty, Usefulness, Technical feasibility, and an environmental factor of Circularity using a four-point scale (0.1, 0.3, 0.7 and 1). Table 1 details the criteria assigned to each value to evaluate the factors. Once the concepts have been evaluated according to each factor, the measurement is performed using equation (1) (Eq (1)):

$$(em) = N \text{ x } U \text{ x } T \text{ x } C. \tag{1}$$

Where (em) means “eco-materials”, (N) means “Novelty”, U means “Usefulness”, T means “Technical feasibility”, and C means “environmental factor of Circularity”

Thus, the concept with the highest score with respect to the evaluated factors is identified.

3. Results

3.1. First stage: Tomato stems: characterization and identification of materials with similar characteristics

Tables 2 and 3 show the average of all the results obtained through the physical, mechanical and chemical characterizations of the tomato stems.

Table 2
Average results of the physical characterization of dried tomato stems from crops S3 and S4.

Physical characterization	Avg. Values
[a]Length (m)	6.18
[a]Weight (kg)	0.933
[a]Diameter (m)	0.0133
[a]Total moisture content (%)	89
Density (kg/m^3)	300–580
Degradation in soil (months)	2
Outdoor degradation (months)	9
Water absorption capacity (%)	372
Ash content (%)	14–18
Thermal conductivity (W/m °C)	0.0582–0.0602
Heat capacity (J/kg °C)	860–1050

[a] Considering fresh stems.

3.1.1. Physical characterization

The average results show (Table 2) that the length of the tomato stems is 6.18 m (see the avg. max. and min. values in Appendix B). This measurement is for an average crop length of 182 days. However, the weight of a fresh stems averaged 0.93 kg, and after 2 months of natural drying, the average weight of dry stems was 0.13 kg; that is, 14% of the original weight. The average diameter of a fresh tomato stem is 1.33 cm. However, the average diameter along the stem is irregular, as can be observed in Fig. 2 (the avg. data per crop can be reviewed in Appendix B).

Average density of the tomato stems is 440 kg/m^3, water absorption capacity is 372%, and moisture content is 89%, similar to the 80% reported for the S1 crop by Llorach-Massana et al. (2017a). By contrast, Zhang et al. (2016) shows that the average moisture content for the middle part of the stem is 64% for tomato stems harvested during the mature period, in July. The ash content is 16% on avg., while Llorach-Massana et al. (2017a) reported a 12% avg for

Table 1
Criteria assigned to each value to evaluate the factors. Adapted from López-Forniés et al. (2017).

FACTOR	CRITERION	SCORE	MEANS
Novelty (N)	High	1	The product derived from the concept will be new to the market; does not exist or cannot be compared with other products on the market.
	Medium	0.7	The concept already exists in the market but not using biomass or woody material and using these materials as a novel material could provide a conceptual difference to the market.
	Low	0.3	The concept is made from biomass or woody material and is already on the market, but for other applications or new for a specific application.
	Without	0.1	The concept is made of biomass or woody material and exists for the same application but differs in some respects.
Usefulness (U)	High	1	The concept solves an existing problem or is the solution for a new application.
	Medium	0.7	The concept solves part of an existing problem independently or the concept only applies to certain aspects of the solution.
	Low	0.3	The concept solves part of a problem under certain circumstances, depending on external factors.
	Without	0.1	The concept solves part of a problem under certain circumstances, but that problem has already been solved in an alternative and simpler way.
Technical feasibility (T)	High	1	Easy to achieve, can be performed using a DIY approach in the same place where the material is generated without an investment.
	Medium	0.7	The implementation of the concept requires some investment and possibly delays in production time and is performed in the same place where the material is generated.
	Low	0.3	The changes are relevant/important, and a high level of investment is needed. Technological implementation can be a problem.
	Without	0.1	The necessary structural or radical changes are difficult to achieve, and the need for investment is very high. Solutions will be time consuming.
Environmental factor of circularity (C)	High	1	Easy to achieve, the material is fully used. The new application ensures a low degree of material degradation, so its use will be maintained over a long time.
	Medium	0.7	The degree of material use is high, in that more than 50% of it is used. The material in the new product will remain in use for a long time.
	Low	0.3	The degree of material use is medium, in that less than 50% of the waste is used. The application of the material to the concept does not ensure prolonged use due to environmental issues (humidity, sunlight, etc.).
	Without	0.1	The degree of material use is limited, at less than 20% of the total. The functionality of the concept will be ephemeral, so the use of the reused material will be as well.

Table 3
Average results of the chemical and mechanical characterization of tomato stems from crops S3 and S4.

Chemical characterization (on the dry matter)	Avg. Values	Chemical characterization (on the dry matter)	Avg. Values
Cellulose content (%)	30–40	Molybdenum (mg/kg)	0.6
Lignin content (%)	5–14	Chromium (mg/kg)	<0.1
Hemicellulose content (%)	4–11	Nickel (mg/kg)	<0.5
Elementary carbon (%)	40.12	Lead (mg/kg)	<0.5
Elementary nitrogen (%)	2.38	Cadmium (mg/kg)	<0.1
Phosphorus (%)	0.89	Silicon (mg/kg)	49.5
Potassium (%)	5.08	Aluminum (mg/kg)	16.22
Calcium (%)	1.5	Selenium (mg/kg)	<2
Magnesium (%)	0.19	Arsenic (mg/kg)	<1
Sulfur (%)	0.37	Mercury (mg/kg)	<0.4
Iron (mg/kg)	50.83	Mechanical properties	Avg. Values
Zinc (mg/kg)	76.5	Young's modulus (GPa)	0.82–2.41
Copper (mg/kg)	12.5	Elongation (%)	3–6
Manganese (mg/kg)	35.83	Ultimate tensile strength (Mpa)	378–791
Boron (mg/kg)	19	Yield strength (Mpa)	1.58–3.86
Sodium (mg/kg)	1451.67	Tensile strength (Mpa)	10.20–34.32

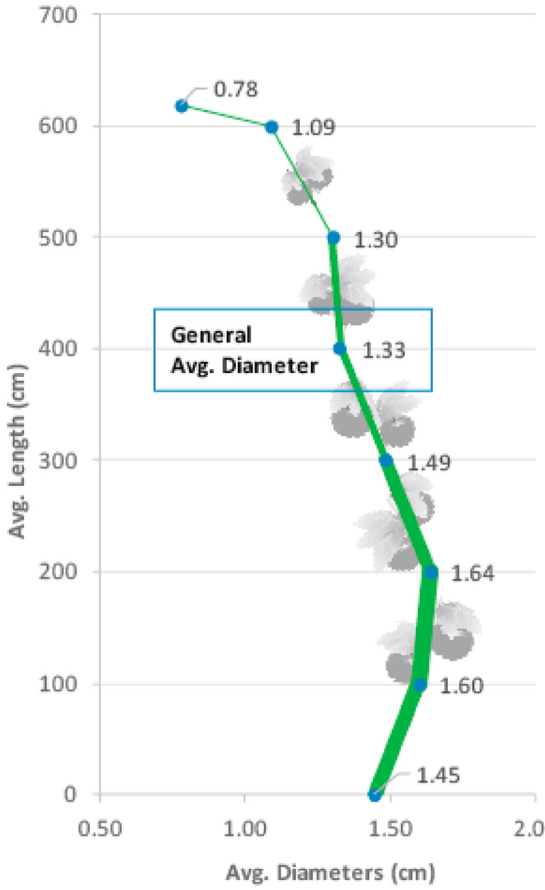


Fig. 2. Average stem: avg. length, avg. diameters depending on height and general avg. diameter.

the S1 crop with a 164-day duration. The thermal conductivity was 0.0592 W/m °C avg. and the specific heat capacity was 955 J/kg °C avg.

Average results of the soil degradation test (Fig. 3) for fresh stems after eight months show that the stems lose an average of 82% of their weight at a constant rate during the first 45 days, as well as their internal structure, making it more fragile. Later, the loss is slower until reaching a constant weight after four months, with a total loss of 90% avg. of the initial weight (Fig. 4). Notably, the results of the soil degradation test on dry stems at five months shows that the stems gain 313% avg. of their weight constantly during the first 15 days by absorbing moisture from the soil. Later, they lose 43% avg. of the weight during the following 15 days, reaching slightly higher weights than the initial ones. From the first month they begin to lose weight more slowly, in addition to the internal structure, making it more fragile, reaching a constant weight at four months with a total loss of 55% avg. of the initial weight.

Fig. 5 shows the average evolution of the three dry stem samples from the outdoor degradation test, starting from natural drying for two months (indoors). During the first 15 days, the stems lose 60% of their weight as well as their flexibility. After one month, the stems have already lost 80% of their weight and in the following month, they lose 6% more, reaching a stable weight from natural drying. Starting from dry stems, the result of 12 months of outdoor degradation shows that dry stems lose 52% avg. of their weight constantly as well as their internal structure, making them more fragile, until they reach a constant weight at nine months. Tomato stem samples at the end of the tests can be observed in Fig. 6, and detailed data on the degradation tests can be found in Appendix B.

3.1.2. *Chemical characterization*

The average results (Table 3) show that the cellulose content was 35.4%, a higher value than the 28.8% avg. reported by Llorach-Massana et al. (2017a). The avg. lignin content is 9.5%, lower than the 19.9% avg. reported by Llorach-Massana et al. (2017a). The hemicellulose content is 9.8% avg., and the 8.2% value obtained by Llorach-Massana et al. (2017a) is very similar (the average values per crop can be reviewed in Appendix B). Nisticò et al. (2017) refer to the chemical characterization of "Postharvest tomato plant" without detailing the part of the plant or giving data regarding the crop from which it comes, but they presented very similar results, with 33% cellulose, 8% lignin and 11% hemicellulose, indicating its low solubility in water (22%).

The averages from the elemental analyses (Table 3) show that carbon content (C) was 40.1% and nitrogen (N) content was 2.38%, while Llorach-Massana et al. (2017a) found 35.7% C content. Nisticò et al. (2017) reported 36.4% C and 3.5% N contents. Toxic elements were below the detection limits (averages for elemental analysis per crop can be reviewed in Appendix B).

3.1.3. *Mechanical characterization*

Mechanical characterization of tomato stems showed values between 0.82 and 2.41 for Young's modulus (GPa), similar to the 0.802 to 1.558 (GPa) reported by Zhang et al. (2016). We found 4%

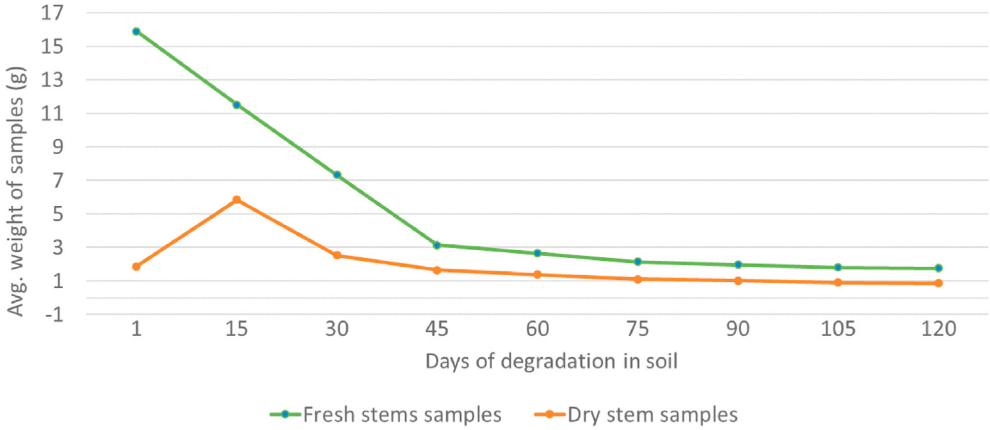


Fig. 3. Soil degradation test in samples of fresh and dry tomato stems.

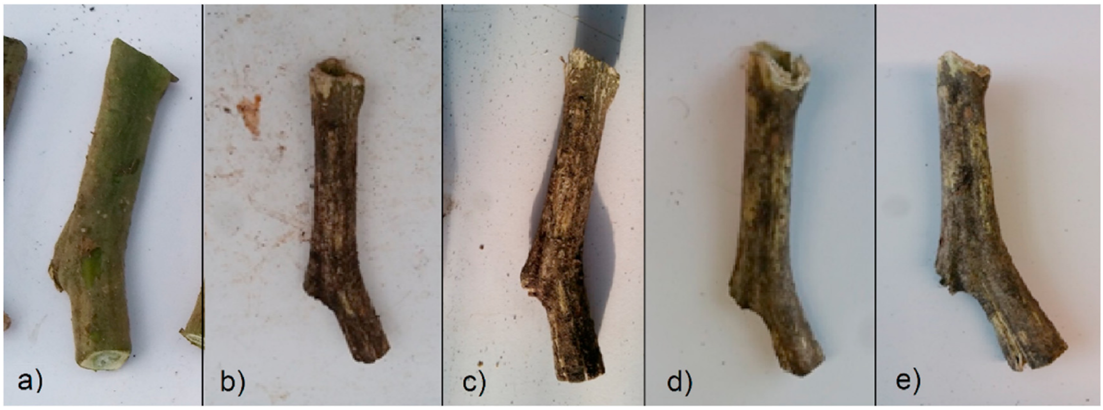


Fig. 4. Evolution of sample 2 from the soil degradation test on fresh tomato stems: a) Fresh stem; b) 1 month degradation; c) 2 months of degradation; d) 3 months of degradation; and e) 4 months of degradation.

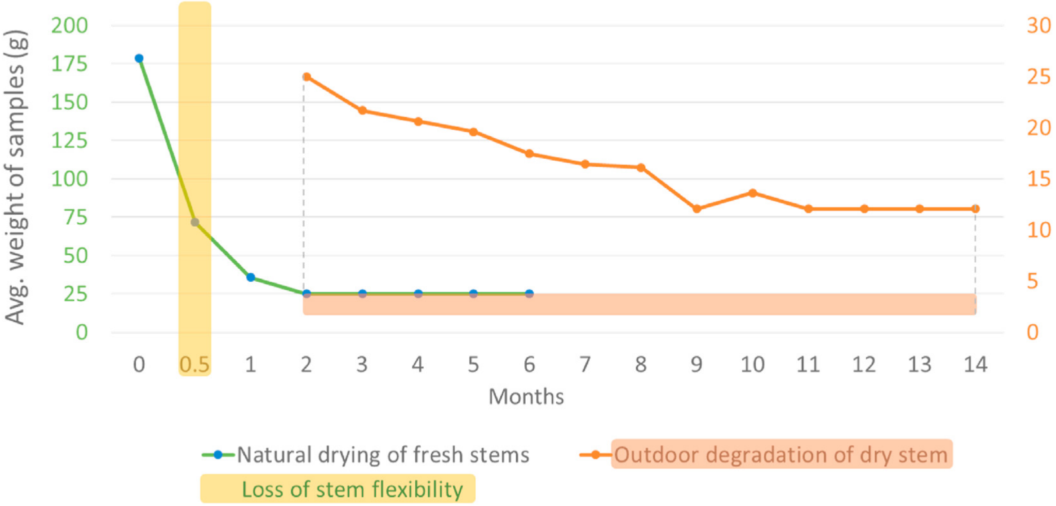


Fig. 5. Outdoor degradation test on dried tomato stem samples starting from natural drying (indoors).

elongation, ultimate tensile strengths (Mpa) between 378 and 791, yield strengths (MPa) between 1.58 and 3.86 and tensile strengths (MPa) between 10.20 and 34.32, while for Zhang et al. (2016), values ranged from 13.73 to 22.68 (MPa) (detailed data by sample can be reviewed in Appendix B).

3.1.4. Identification of materials with similar characteristics

According to results of stem characterization, several natural fiber-like materials with some similar characteristics were identified (see Appendix B). However, according to the graphic method for material selection, stems showed greater similarities to other

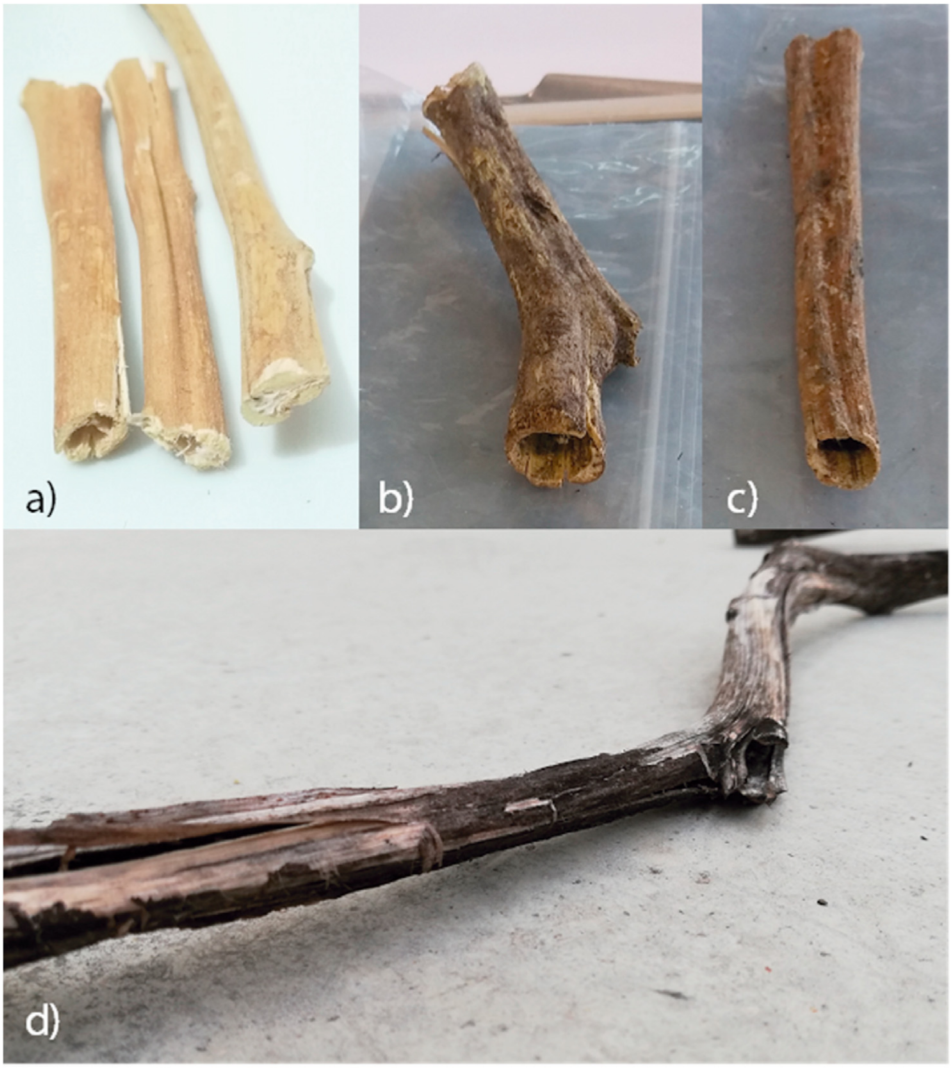


Fig. 6. Tomato stem samples at the end of the tests: a) Natural drying, b) Fresh stem degradation in soil, c) Dried stem degradation in soil, and d) Degradation outdoors.

natural materials, to the family of “woods or wood-type materials”, than to the “natural fibers” category (Fig. 7).

As shown in Fig. 8, the combination of four Ashby graphs show that materials with the greatest similarity to stems appear within the circular areas indicating properties used for each case, while areas within the squares indicate the degree of general similarity to tomato stems (Ts) (see detailed information in Appendix B). The material with the highest similarity overall was “Willow, along grain (W-L)” followed by “Pine, across grain (P—C)”, “Palm, along grain (Plm-L)”, “Pine, along grain (P-L)” and “Spruce, across grain”. All of them came from the “wood or wood type materials” group. Typical uses of this type of material are furniture, containers, building construction, floors, boxes, doors, frames, and decorative objects, among others (GrantaDesign© 2018).

3.2. Second stage: Creative eco-ideation session

This section is divided into “Generation and selection of concepts” and “Concept evaluation in the creative session” sections.

3.2.1. Generation and selection of concepts

The objective of the creative session was to generate concepts to identify applications for tomato stems. According to the above, the workshop structure allowed, first, in a divergent way, the participants to generate the greatest number of concepts and then, in a convergent way, to specify the concepts to obtain those with the greatest potential to develop and later be evaluated.

Fig. 9 shows the specialties of the five participants who made up each group on the dynamics of concept generation. Based on the bibliographic information and the results of stem characterization, the pairs of terms used in the “forced relationships” technique can be observed in Table 4. Details on the dynamic results can be reviewed in Appendix B.

In accordance with the tools described in the methodology, such as “forced relationships”, the concepts described in Fig. 10 were generated, and the results of the concept development dynamics are included using key questions. Although each group worked and selected different pairs of terms, both groups agreed on “Containers and Packaging” as one of the resulting concepts. For Group 1, the next resulting concept was “Multifunctional screens or fences” and for Group 2 it was “Multifunctional panels or blocks".

3.2.2. Concept evaluation in the creative session

The three final concepts on applying the stems and the results of the qualitative evaluation are shown in Fig. 11.

Considering that each participant had nine votes among the

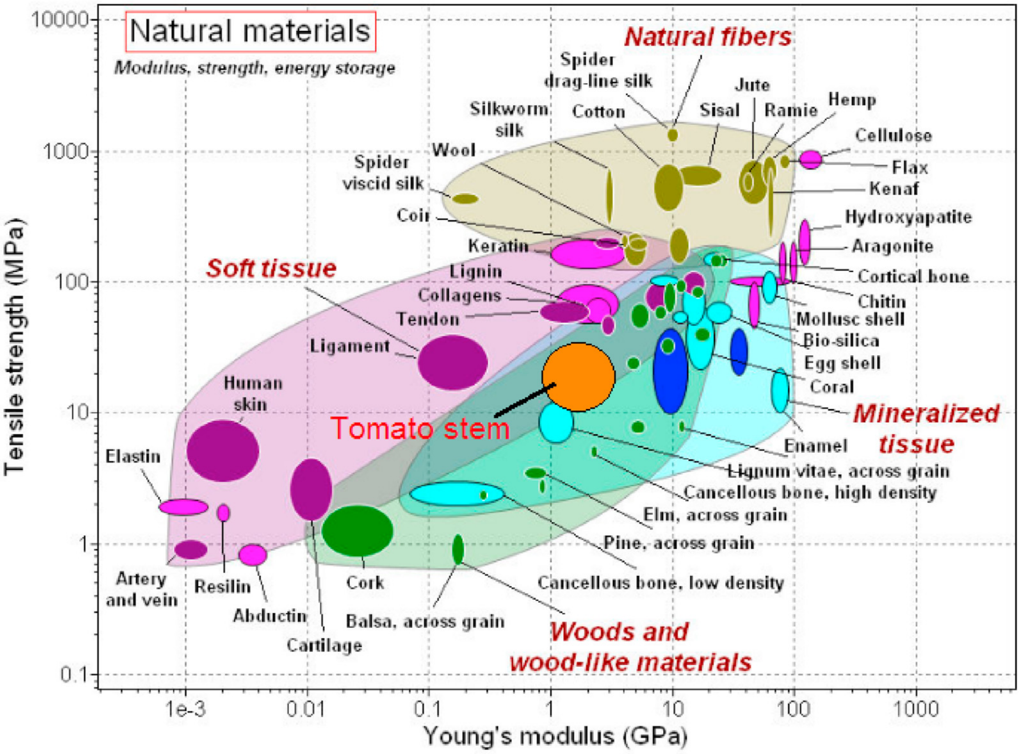


Fig. 7. Ashby graph of tensile strength/Young's modulus values for natural materials. Adapted from (Ashby 2008) with tomato stem values added indicated in orange.

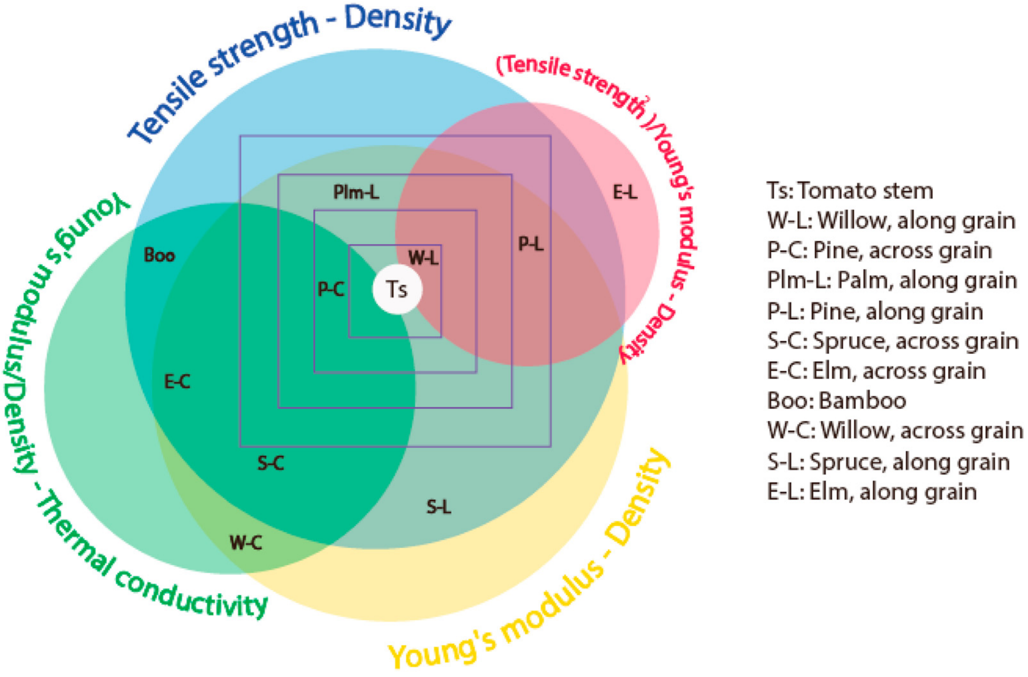
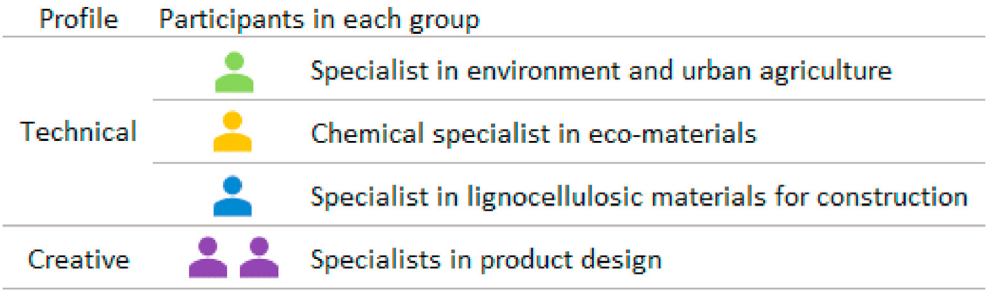


Fig. 8. Combination of results from four Ashby graphs to identify materials with characteristics similar to those of tomato stems.

positive, negative and interesting evaluations, there was a total of 90 votes. However, only 69 votes (77%) were used. The concept that received the most votes in general was “Boards, panels and blocks (C3)" with 26 votes, with 11 negative, 10 positive and 5 interesting. The concept “Fences and trellises (C1)” followed with 23 votes, with 10 interesting, 7 negative and 6 positive. Finally, the “Packaging (C2)” concept received 20 votes, with 8 positive, 6 interesting and 6 negative. Concept C3 was the one with the highest number of positive votes primarily due to the environmental criterion followed by the market impact criterion. However, it was also the proposal with the highest number of negative votes, surpassing the positive ones, primarily in the technical feasibility criterion.



Profile	Participants in each group
Technical	Specialist in environment and urban agriculture
	Chemical specialist in eco-materials
	Specialist in lignocellulosic materials for construction
Creative	Specialists in product design

Fig. 9. Profile and specialty of the participants in the creative session by group.

Table 4
Terms used for the “force relationship” technique during the dynamics of concept generation.

Physical property	Market of application
Lightness	Building
Lignocellulosic	Automotive
Buoyancy	Decor
Woody	Furniture
Thermal insulator	Packaging
Biodegradable	Gardening
Sustainable	Home
Rigid	Agriculture (urban)
Compressible	Textile
Sawdust can be made	Fashion

However, concept C1 was the one with the highest number of interesting votes in the technical feasibility criterion. The C2 concept was the one that generally had an average valuation, being the only concept without a negative vote in one of the criteria, which was the environmental one. The comments on each evaluation for each concept can be reviewed in Appendix B.

3.3. Third stage: Tests and evaluation of viable applications for tomato stems as eco-material

Different tests were performed on the tomato stems based on the concepts generated through the creative session, which involve two primary processes. The first is braiding, which was considered for the “Fences, trellises” concept, and the second process is crushing, considered for “Packaging” and “Boards, panels, blocks”. This process was used to visualize the performance of the stems as eco-material in a practical way and later, together with the information obtained in the creative session, to evaluate the three final concepts semi-quantitatively, in a more accurate way.

3.3.1. Tests with tomato stems as eco-material

To test the braiding process, fresh stems were used because they maintain their flexibility before the first 15 days (Fig. 5) after cutting, and they were manually manipulated to bend them in different ways. The result was positive, to create circular bends with a diameter of not less than 70 cm, since making a tighter bend causes it to begin to break. Interestingly, an attempt was made to create lattices with the stems measuring approximately 5 m^2, but it was complicated because the stems were not completely straight, in addition to having knots (where the branches were cut) that make tissue manipulation difficult. A three-stem braiding test was performed, which was done manually without much difficulty (Fig. 12). It was hung on one end and a 10 kg weight was added at the other end to identify its resistance for 2 weeks in the RTG. During that time, the stems were drying and thinning. However, the result was positive since the stems did not show signs of rupture during that time.

Considering the results of the different degradation tests that show that the stems become fragile and brittle when they lose their internal structure completely, the naturally dried stems, despite losing moisture, had preserved internal structures and therefore retained their resistance.

The crushing process was previously tested to perform two experimental lettuce cultures using the tomato stems as substrates. Approximately 13.5 kg of dry stems were crushed, yielding fiber lengths between 0.5 and 10 cm, which was characterized for use as a substrate (Manríquez-Altamirano et al., 2020). In this way, we identified great similarity regarding the shared tomato stem characteristics and properties compared with common wood chips. Therefore, processes such as compaction by temperature or natural binders could be possible.

3.3.2. Semi-quantitative evaluation of results

The results of the semi-quantitative evaluation show (Table 5) that the application concept for the tomato stalks that had the highest score was C1. The best evaluation was high for the factor of “T", and the worst was “U", while there was an average evaluation for the “N" and “C" factors. The C2 concept ranked second, with a mean evaluation for factors “U” and “T” factors and a low evaluation for “N” and “C”. By contrast, the concept with the lowest score was C3. The best evaluation was a medium for the “T” factor, low values for “N” and “C”, and the lowest was “U”.

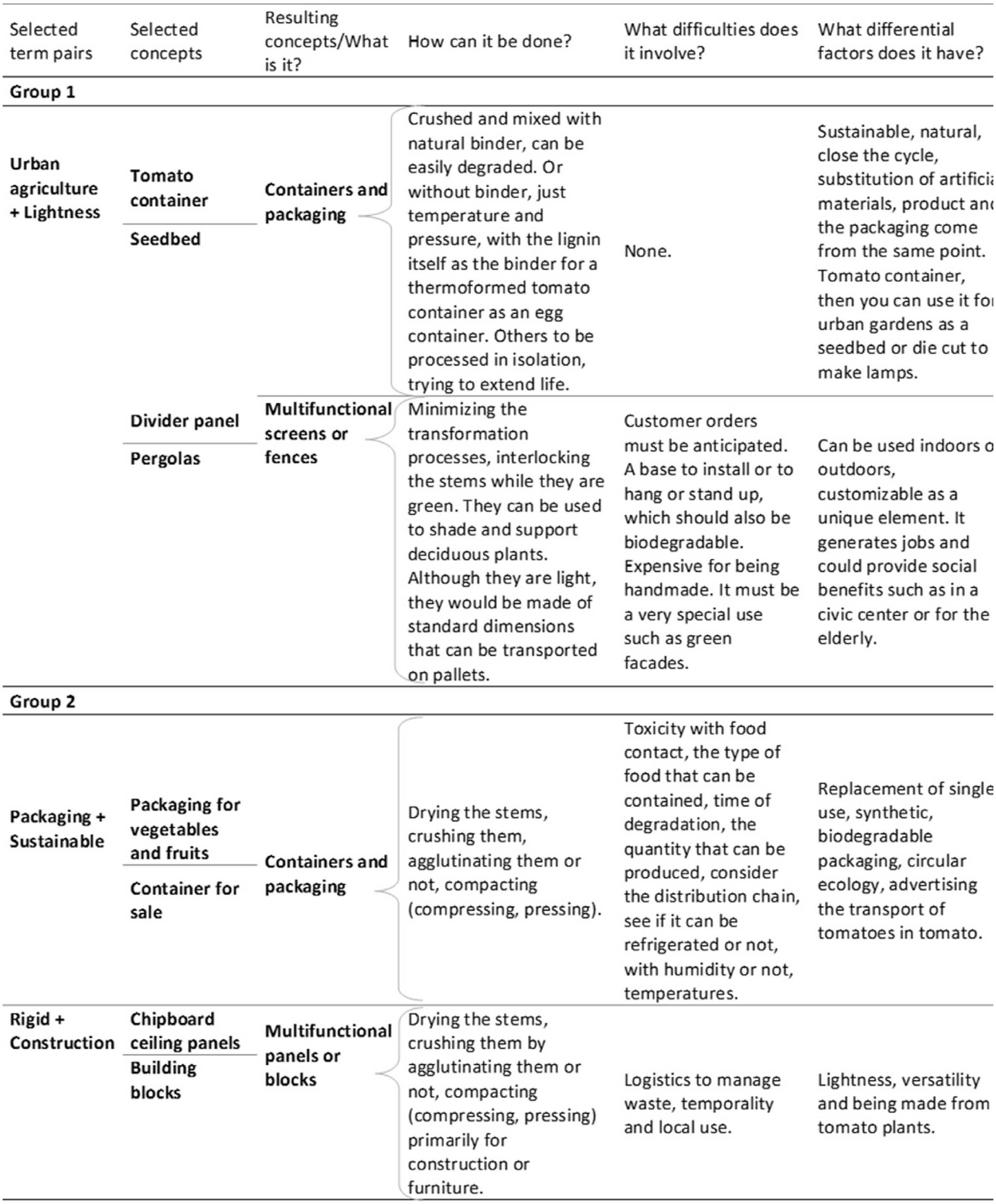
4. Discussion and conclusion

Most studies that contemplate the benefits of UA for the use of waste, focus on UA as a sink for organic waste generated within cities, using it as a substrate (Grard et al., 2018) or as compost to contribute nutrients to the soil (Ferreira et al., 2018; Goldstein et al., 2016). In this sense, it is not yet fully considered that the UA system itself generates SW, mainly organic.

In accordance with the existing body of knowledge, this study is the first one to propose a methodology for the local use of a residual biomass generated by urban agriculture.

Unlike traditional use of biomass, such as composting, this study aims to find applications that add value to residual biomass for use as a higher quality eco-material without losing the benefits of its processing and use locally. By means of the methodology used, three possible applications were generated for tomato stems, which according to the results of the semi-quantitative evaluation are ordered as follows “Fences and trellises”, “Packaging” and “Boards, panels and blocks”. Thus, the fixation of CO2 is promoted for a longer time, helping to improve environmental performance of the UA’s life cycle and reduce the volume of potential OSW within cities.

Furthermore, this study provides information on the physical, chemical and mechanical characterization of tomato stems that



Selected term pairs	Selected concepts	Resulting concepts/What is it?	How can it be done?	What difficulties does it involve?	What differential factors does it have?
Group 1					
Urban agriculture + Lightness	**Tomato container** **Seedbed**	**Containers and packaging**	Crushed and mixed with natural binder, can be easily degraded. Or without binder, just temperature and pressure, with the lignin itself as the binder for a thermoformed tomato container as an egg container. Others to be processed in isolation, trying to extend life.	None.	Sustainable, natural, close the cycle, substitution of artifici materials, product an the packaging come from the same point. Tomato container, then you can use it fo urban gardens as a seedbed or die cut to make lamps.
	Divider panel **Pergolas**	**Multifunctional screens or fences**	Minimizing the transformation processes, interlocking the stems while they are green. They can be used to shade and support deciduous plants. Although they are light, they would be made of standard dimensions that can be transported on pallets.	Customer orders must be anticipated. A base to install or to hang or stand up, which should also be biodegradable. Expensive for being handmade. It must be a very special use such as green facades.	Can be used indoors o outdoors, customizable as a unique element. It generates jobs and could provide social benefits such as in a civic center or for the elderly.
Group 2					
Packaging + Sustainable	**Packaging for vegetables and fruits** **Container for sale**	**Containers and packaging**	Drying the stems, crushing them, agglutinating them or not, compacting (compressing, pressing).	Toxicity with food contact, the type of food that can be contained, time of degradation, the quantity that can be produced, consider the distribution chain, see if it can be refrigerated or not, with humidity or not, temperatures.	Replacement of single use, synthetic, biodegradable packaging, circular ecology, advertising the transport of tomatoes in tomato.
Rigid + Construction	**Chipboard ceiling panels** **Building blocks**	**Multifunctional panels or blocks**	Drying the stems, crushing them by agglutinating them or not, compacting (compressing, pressing) primarily for construction or furniture.	Logistics to manage waste, temporality and local use.	Lightness, versatility and being made from tomato plants.

Fig. 10. Concept selection process and developing resulting concepts using key questions.

could be useful for other lines of research. There are studies that provide data on different parts of the tomato plant such as the pulp to extract lycopene (Rath & Olempska-Beer, 2007), peels and seeds for the production of biodegradable pots (Schettini et al., 2013) or the complete plant together with leaves and branches for the production of polyethylene-co-acrylic acid films and soluble biopolymers (Franzoso et al., 2015), to study the uptake and distribution of metals by tomato plants (Trebolazabala et al., 2017), and to study its leaves as a source of metabolites (Junker-Frohn et al., 2019). However, there are few studies that provide data on the stems of tomato plants in particular and have different approaches, for example for the development of harvesting and processing machinery (Zhang et al., 2016), to study the yield, growth and characteristics of the stems through their physical stimulation comparing the vertical or horizontal training of the stem (Ohta and Makino, 2019), for the development of a growth model of the stem diameter to predict the growth response of the plants under different conditions (Qin et al., 2017). For its use, but together with the rest of the parts of the plant, studies were found to create plastic films (Nisticò et al., 2017) or as a bio-chart (Llorach-Massana et al.,

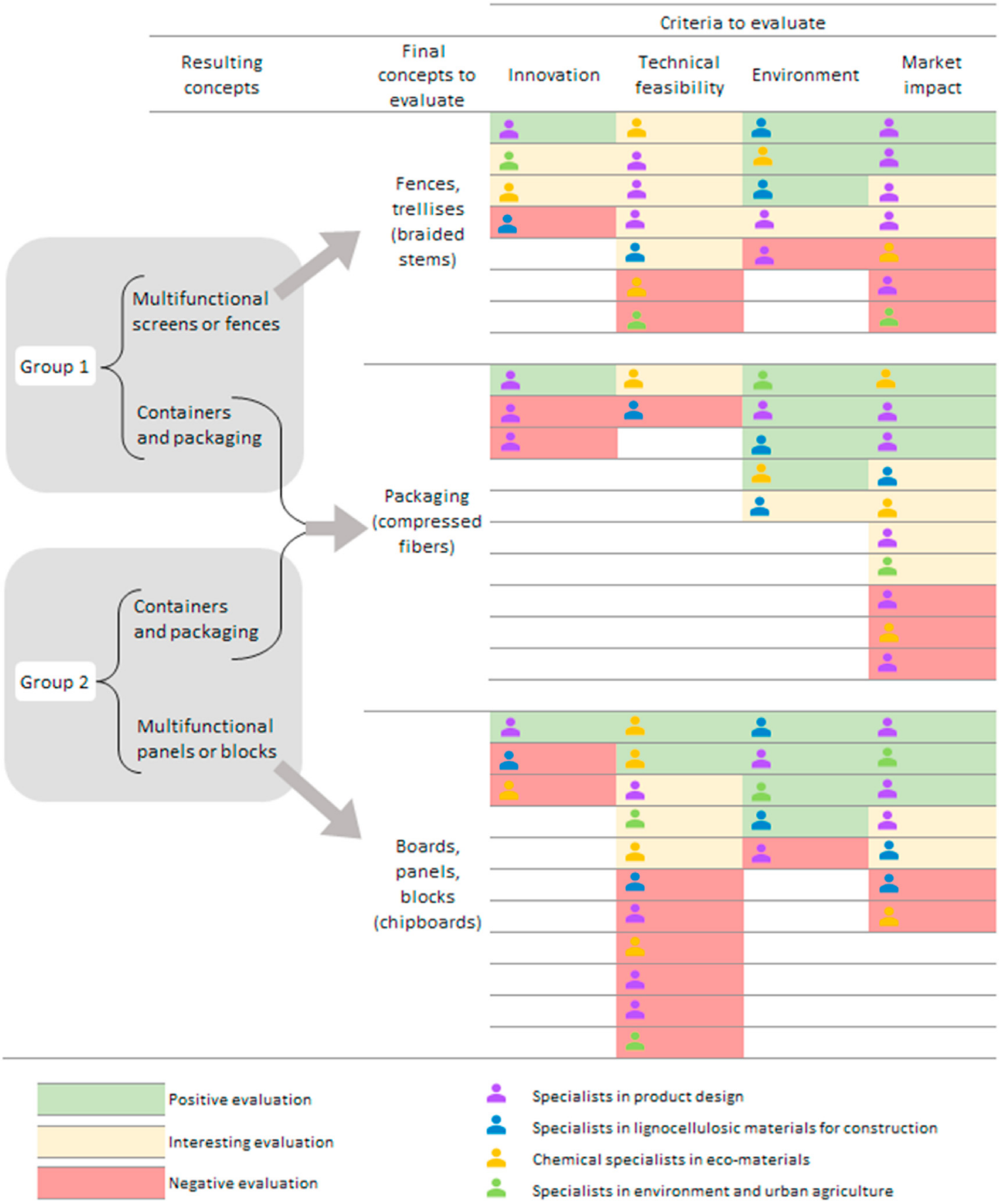


Fig. 11. P–N–I Evaluation of resulting concepts according to the specialization of the participants.

2017a).

Only two studies were found where tomato stems are used in particular, although mixed with other materials in different proportions, for the production of paper through the cooking process (Üner et al., 2016) and for the renewable material of thermal insulation production (Llorach Massana, 2017).

Although tomato crops are one of the most widespread in Europe within conventional agriculture and one of the crops that produces the most residual biomass, no study was identified that collected data particularly on stems for their use. This research could also provide useful data for use on this scale, which would imply expanding the possibilities regarding its management and processes, always considering a prior environmental assessment.

As mentioned above, in conventional agriculture, in general, large volumes of SW generated are considered, so it is possible that its use by more complex processes such as chemicals for the production of eco-materials is an alternative with less environmental impact to make products with other materials. Performing an environmental assessment using methodologies such as LCA can be a good way to verify it (Turner et al., 2016).

However, the case of AUSW at the local level (building, neighborhood) is different since, by generating less volume of waste than conventional agriculture, there are processes that may not be viable. Hence, its use as an eco-material is reduced to its elaboration with very basic or simple processes such as those promoted by the DIY approach.

Fig. 12. Braiding and resistance test of tomato stems: a) Braiding process; b) fresh braided stems carrying weight; and c) detail of braided dry stems.

Table 5
Evaluation of final concepts using four-point scale metrics.

	Factors to evaluate				Final score	Ranking
Final concepts	N	U	T	C	em	#
Fences and trellises (C1)	0.7	0.1	1	0.7	0.049	1
Packaging (C2)	0.3	0.7	0.7	0.3	0.044	2
Boards, panels and blocks (C3)	0.3	0.1	0.7	0.3	0.006	3

N: Novelty, U: Usefulness, T: Technical feasibility, C: environmental factor of Circularity and em: eco-materials.

The results presented in this study show that the use of the methodology proposed is useful to identify possible applications to upcycle AUSW *in situ*. Mainly by the use of creative techniques that, in addition to generating innovative ideas, allow flexibility in the methodology for its effective adaptation, since the level of detail and particularity increases as the study area becomes smaller and local.

On the other hand, it is also important to consider in this creative process, in addition to the specialists, the people who interact in the space, either directly in the crop or those who use the building who could be possible users of viable applications of stems. This perspective could help visualize other local needs that could be addressed using AUSW.

The DIY approach was helpful when considering simple processes, techniques and tools by which AUSW can be recycled while retaining the benefits of local use. Currently, there are studies in which the DIY approach is applied to create eco-materials (Rognoli et al., 2015), for example, treating potato residues (Caliendo et al., 2020) or peanut shells to create bioplastics (Troiano et al., 2018). This approach also allows designers to experiment with new materials and processes by creating interdisciplinary links that drive eco-design.

Therefore, this study intends to offer a guide regarding an interdisciplinary methodology adaptable to other circumstances and contexts to take advantage of the AUSW that, as mentioned above, are different in terms of their composition and volume for each case.

Beyond considering the use of AUSW through DIY techniques as a limitation, the advantages that this implies must be considered. One of these advantages would be to be able to create socio-cultural dynamics at the local level, such as the implementation of workshops or courses that allow the development of eco-products with the AUSW to make the population aware of the importance of reducing waste within cities as well as reinforcing the message of self-production and self-sufficiency that continues from the UA itself.

Then again, the creation of networks between neighborhoods or nearby communities could also be considered to exchange resources, not only for production, but also for AUSW or eco-products creating synergies to cover self-sufficiency needs (Keng et al., 2020; Rognoli et al., 2015).

An initiative that is gaining momentum in terms of self-production and self-consumption at the neighborhood level by sharing resources and knowledge are the “Fab labs” (Bridgens et al., 2018; Prendeville et al., 2018) that function as a network of public workshops that provide access to machinery, tools and advice to the community. This type of initiatives focused on DIY could help to materialize the concepts chosen for the use of AUSW as eco-materials in eco-products.

CRediT authorship contribution statement

Ana Manríquez-Altamirano: Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization. **Jorge Sierra-Pérez:** Conceptualization, Methodology, Writing - review & editing, Visualization, Supervision. **Pere Muñoz:** Methodology, Writing - review & editing, Supervision. **Xavier Gabarrell:** Conceptualization, Methodology, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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the Barcelona School of Design and Engineering (ELISAVA).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.126360.

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