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Spatial analysis to quantify and localise the residual cardoon stem fibres as potential bio-reinforcements for building materials

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ABSTRACT

Today in Europe building-sector is responsible for the 50% of air pollution and for 70% of waste production. For this reason, researchers' interest is focused on new eco-building materials that are sustainable, with low impact, renewable and recyclable. In this context, in the last few years, the use of cellulose-based fibres as potential reinforcements for bio-composite materials, instead of synthetic one, received worldwide growing attention. Among natural fibres, both cellulose and protein-based ones, in literature it was found that, due to its mechanical properties, artichoke fibre is suitable for this use. In this study, a Geographical Information System (GIS) – based model to locate and quantify the yearly amount of agricultural waste coming from *Cynara cardunculus* L. (CW) cultivation was put forward and was applied in a study area located in Southern Italy. As an additional protein-based fibre, sheep wool fibre was also taken into account due to the high presence of sheep. The estimated available amount of both considered fibres was reported in a GIS map in order to show their distribution at territorial level. The achieved results could represent basic information for both sustainable locating collection centre and analysing the environmental impact related to the logistics and supply phase.

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Natural fibres; *Cynara cardunculus* L.; GIS-based model; circular economy; sustainability

1. Introduction

Nowadays, building sector is the most responsible for environmental degradation, global warming, and climate change (Ingrao et al. 2016). In fact, at a worldwide level, about 50% of carbon emissions, 20–50% of consumption of energy and natural resources, and 50% of total solid waste production (Vasilca et al. 2021; Barreca et al. 2018) are generated by construction industry. Ecological concerns such as environmental safety and recyclability have resulted in an increasing interest in green materials (Sain and Panthapulakkal 2004). Furthermore, discovering new alternatives for materials derived from non-renewable resources is urgently needed (Ingrao et al. 2019). In this regard, recently several studies are focused on new resources and sustainable materials that could be involved and integrated into building process (Sarasini and Fiore 2018).

With the aim of replacing traditional building materials, e.g. concrete, steel, plastics' component, by using new eco-friendly materials, contributes significantly to reduce the impact on environment, by reducing CO₂ emission, air and water pollution, waste solid production, and saving energy (Asdrubali, D'Alessandro, and Schiavoni 2015). Since the eco-friendly materials are generally obtained by using natural and renewable sources that are not commonly employed for construction (Moussa et al. 2018), they are totally recyclable, sustainable, non-toxic for human health, with a low carbon foot (Ingrao et al. 2015). Moreover, fully in accordance with the circular economy statements, eco-building materials could be also obtained by the reconversion of wastes (Aarhus 2015).

By considering this conversion to a green building approach, the interest in bio composites is constantly grown. A bio composite is a material composed of a matrix added by one or more distinct constituent materials, generally reinforcement fibres. These two or more constituents are combined to realise a new material with performant physical and mechanical behaviours (Fagone et al. 2019) or to improve the quality of recycled coarse concrete aggregates (Gonzalez and Etxeberria 2014; Singh et al. 2021).

Recently, the use of natural fibres as reinforcement for composite materials, instead of synthetic ones (e.g. glass fibre, polymeric fibres), is receiving increasing attention not only for their mechanical properties, but also for the low cost, the recyclability, the availability, and for health benefits that come from their use (Mathur 2006; Liuzzi, Sanarica, and Stefanizzi 2017; Fagone et al. 2019; Galan-Marin, Rivera-Gomez, and Garcia-Martinez 2016; Rojat et al. 2015). There is a wide variety of different natural fibres which can be applied as reinforcements. Furthermore, the use of agricultural residues provided also a solution to solve problems concerning solid waste disposal, which usually does not have any economic alternative (Vitrono et al. 2021). The most widely cellulose-based fibres used are flax, hemp, jute, kenaf and sisal, because of their properties and availability; only few recent scientific works have analysed the feasibility to use other cellulose-based fibres, such like okra (De Rosa et al. 2010) and isora (Mathew, Joseph, and Joseph 2006), as reinforcement for bio-composite materials. Three types of fibres, wheat straw, barley straw and wood shavings, were investigated by (Ashour and Wu 2010) as reinforcement on plaster materials that also are composed of cohesive soil and sand.

Worldwide, researchers are working to investigate the potential use of natural fibres as reinforcement composites by analysing their properties like tensile strength, compressive strength, toughness, thermal degradation temperature, low weight (Sanjay et al. 2018; Raja et al. 2017). Protein-based fibres are of animal origin (e.g. pig hair, sheep wool, silk) or vegetables (e.g. cotton, hemp, linen, jute, sisal, coconut, bamboo, cork), and differ by their structure. In detail, animals' fibres have a protein structure (i.e. keratin protein); instead, plants' fibres are composed by a lignocellulose structure (i.e. cellulose, lignin, hemicellulose, pectin, waxes, and water-soluble substances), which contributes at improving the tensile strength of vegetable fibres.

Among cellulose-based fibres, thanks to its mechanical characteristics, *Cynara cardunculus L.* fibres (CW) are well suited to building applications as reinforcement for adobe clay or cement mix. Several research studies were carried out on globe artichoke due to its relevant production and due to the several uses different from human food, i.e. fresh biomass, forage for livestock, feedstock for the preparation of alcoholic beverages, and a source of inulin (Lo Giudice et al. 2014).

Several research studies have revealed the possibility of using this kind of biomass (leaves, stems, flower heads and achenes) as solid biofuel, through direct combustion or pyrolysis (Damartzis et al., 2011; Ierna et al., 2012; Karampinis et al., 2012). Few studies have investigated the possibility of using CW as a new and alternative feedstock for anaerobic digestion for biogas production (Ferrero et al. 2020), by demonstrating that the chemical characteristics, in terms of tissue lignification, could affect biogas plant management at the farm scale (Foti et al. 1999) and, moreover, could arise environmental, social and economic concerns related to the competition between food and non-food products, i.e. the use of cardoon for human food, energy crops and for industrial purposes, by disregarding the Biogasdoneright© concept (Dale et al. 2016; Valenti et al. 2016; Selvaggi et al. 2018; Selvaggi and Valenti 2021).

Instead, in order to investigate the possibility of using globe artichoke cellulose-based fibres as reinforced composites, Fiore, Valenza, and Di Bella (2011) carried out an experimental trial for the identification of microstructure, chemical composition and mechanical properties of cardoon stem fibres, with the aim of evaluating their potential use as reinforcements for polymer composites. By single fibre tensile tests, tensile strength and Young's modulus of cardoon stem fibre were evaluated and the results were analysed through a statistical Weibull distribution, already used for other cellulose-based fibres (Fagone et al. 2019; Thyavihalli Girijappa et al. 2019). Using obtained results comparable to those of other cellulose-based fibres, i.e. banana and sisal fibres (Elanchezhian et al. 2018), it has been demonstrated that artichoke fibres, coming from the recovery of cardoon stems, are suitable to replace synthetic fibres as reinforcement in composite structures.

Nowadays, data on the exact amount of these fibres are very limited. This lack of official data related to the amount of recyclable fibres in terms of volume, and especially to the spatial localisation of the sites where these are produced, are the main factors that have over the years limited their reuse and exploitation. For this reason, this research study aims, by

using Geographic Information System (GIS) tools, to fill the gap in the knowledge of the production, quantification and above all the localisation of CW as potential reinforcement cellulose-based fibres by its recycling process and to support new eco-building material production.

In detail, this research study focused on the first step of post-cultivation management of *Cynara cardunculus L.* wastes, i.e. stems, which is crucial in order to put forward a method for a sustainable recovery management and extracting process of fibres. Worldwide, Italy is the higher producer of cardunculus, and Sicily is the region with the yearly higher cardunculus production, followed by Apulia (Istat 2021). A large amount of waste, about 80–85% of this cultivation ground biomass was produced (Pandino, Lombardo, and Mauromicale 2013). Stems and leaves are the most abundant wastes regarding cardoon crops (Barbosa et al. 2020), and represent the 40% and the 60% of these wastes, respectively (Esposito et al. 2016).

Since GIS tools are a suitable platform for environmentally related issues and have been applied for both assessing, quantifying and site-location analyses, in this study a GIS-based model was developed for collecting, organising, analysing, and visualising geographical data related to CW (Zubaryeva et al. 2012; Höhn et al. 2014; Valenti et al. 2018; Selim et al. 2018; Abbasi, Pishvae, and Bairamzadeh 2020; Zolfaghary, Zakerinia, and Kazemi 2021; Parlato, Valenti, and Porto 2020; Selvaggi et al. 2021).

Data recorded by statistical database were elaborated and applied for quantifying the amount of CW. The obtained results were adopted for computing, through a suitable index, the amount of available cardoon stems and developing tailored heatmaps for showing its distribution at territorial level.

Moreover, cardoon stem fibres yearly amount was also compared with sheep wool fibres yearly amount production. In a recent paper (Parlato and Porto 2020) sheep wool fibre was investigated as new resource for building construction, so it was interesting combining the localisation and the availability of these two different cellulose and protein-based fibres.

The GIS-based model results could provide basic information for the analysis of the environmental impact related to the logistics and supply phase due to the transportation of the estimated amount of fibres from both cardoon stems and sheep wool to a future collection centre for reusing them.

In addition, the use of both cellulose and protein-based fibres as a potential reinforcement in composite materials could also bring important benefits in terms of new jobs, in a region where the unemployment rate is quite high, within the context of circular economy.

2. Materials and methods

2.1. *Cynara cardunculus L.*

Cynara cardunculus L. is a perennial plant belonging to the family *Asteraceae*, which is native to the Mediterranean area, commonly known as cardoon. Fibres of cardoon are generally extracted by stems through a maceration process. Stems of cardoon have a complex structure consisting mainly of cellulose, hemicellulose, lignin, pectin, and other compounds. This

anatomical structure is typical of dicotyledon angiosperm non-woody plant with a central pith surrounded by a cortex and with an irregular thin epidermis (Gominho et al., 2018). Fibres are located on a fibro-vascular bundle that surround the pith. Helically wound microfibrils of cellulose are the constituent of each fibre that are bounded together by an amorphous lignin matrix. In Table 1 is reported a typical chemical composition of cardoon fibre (Fiore, Valenza, and Di Bella 2011):

Mechanical and physical behaviours of cardoon fibres were found in literature. In detail, tensile strength is about 200 MPa, Young's modulus is about 11.62 GPa, diameter is in the range between 150 μm to 320 μm , and density is about 1.579 gr/cm^3 (Fiore, Valenza, and Di Bella 2011). These values are comparable, as shown in Table 2, with those of other vegetable fibres commonly employed in green building sector.

For this reason, cardoon fibres are suitable to be used as reinforcement fibres for bio-composites (Sarasini and Fiore 2018; Turco et al. 2021).

To locate and quantify the yearly amount of waste coming from *Cynara cardunculus L.* a GIS-based model has been developed.

2.2. Study area

Sicily is a Southern region of Italy divided into nine provinces with the Tyrrhenian Sea to the North, the Ionian Sea to the East and the Mediterranean on the remaining coasts. It extends for 25,707 km^2 and, in addition to being the largest Island in the Mediterranean, it is the largest Italian region (Figure 1). Sicily is also the Italian region with the largest extension of agricultural land (Table 3), and as reported by statistical database (Istat 2021) it is the region with the highest production of *Cynara cardunculus L.* (Table 4).

Table 1. Chemical composition of cardoon fibres.

Component	Content (%)
Cellulose	75.3 \pm 1.2
Lignin	4.3 \pm 0.5
Ash	2.2 \pm 0.05

Table 2. Mechanical properties of most common vegetable fibres (Thyavihalli Girijappa et al. 2019).

Fibre	Density [gr/cm^3]	Tensile strength [MPa]	Young's modulus [GPa]
Jute	1.23	325–770	37–55
Flax	1.38	700–1,000	60–70
Hemp	1.35	530–1,110	45
Ramie	1.44	915	23
Banana	1.35	721–910	29
Bagasse	1.20	290	17
Henequen	1.40	500	13
Pineapple	1.50	1,020–1,600	71
Kenaf	1.20	745–930	41
Coir	1.20	140–175	6
Sisal	1.20	460–855	15
Abaca	1.50	410–810	41
Cotton	1.21	250–500	6–10
Nettle	1.51	650	38
Cardoons*	1.58	200	11

* (Fiore, Valenza, and Di Bella 2011)

In Sicily, as in the rest of the South, employment in agriculture is much higher than the national average. Despite the lowest wages, in Sicily agriculture has maintained its predominant position within regional economy (Valenti et al. 2017), with the highest Utilised Agricultural Area (UAA), equal to over 1.387 million hectares which correspond to about 10.8% of the national UAA (Badami, Caracci, and Costanzo 2017).

Data related to the last 5 years (from 2016 to 2020), with reference to horticultural open field crops (both cultivated area and production) and by paying attention to the *Cynara cardunculus L.*, were elaborated at regional level and reported in Tables 3 and 4, respectively, for cultivated area and production.

From the data elaboration, as reported in Table 3, in Italy an average of about 380,000 ha/y of cultivated surface area are dedicated to horticultural crops cultivation, while in Sicily the cultivated surfaces are a little more than 60,000 ha/y (about 15%). Moreover, within the selected time-interval, the horticultural open field crops cultivated areas registered in Sicily a slight increase (+1.1%) by rising from about 59,000 ha/y to 67,000 ha/y.

By paying attention to the Cardunculus cultivation, about the 90% of the Italian cardunculus cultivated area coming from only three regions. Sicily is the region with the highest cultivated area, an average of about 40,000 ha/y, which corresponds to 37% of the Italian cardunculus cultivated area, followed by Apulia and Sardinia with about an average of 12,000 ha/y (30%) and 9,000 ha/y (23%), respectively. By considering the trend during the selected time-interval in Sicily a slight increase (+1.1%) was registered, by rising from about 14,000 ha/y to 15,200 ha/y.

However, Lombardy region contributes to the horticultural cultivated area with an average of about 16,000 ha/y, it is possible to notice that almost no areas were dedicated to Cardunculus cultivation, as well as for Piedmont, Friuli-Venezia Giulia, Valle d'Aosta, and Trentino Alto-Adige regions (Table 3).

Data related to the horticultural open field crop production were elaborated and reported for each Italian region in Table 4, by considering the same time-interval (2016–2020) and focusing on the cardunculus production.

By considering the production, as it shown in Table 4, again Apulia, Emilia-Romagna, and Sicily are those regions with the highest horticultural open field crop production, by representing more than 50% of the total production (about 12 million t/y), with, respectively, an average of about 3 million t/y, 2.4 million t/y and little less than 1 million t/y.

Instead, by focusing on the cardunculus production, Sicily, Apulia and Sardinia regions represent more than 80% of the Italian production (about 390,000 t/y). In detail, in Sicily more than 150,000 t (41% of the total production) were yearly produced. Furthermore, within the selected time-interval, the horticultural field crops registered in Sicily had a slight increase (+1.2%) by rising from about 950,000 t/y to more than 1 million t/y, while the production of cardunculus was kept almost unchanged (Table 4).

As concerning other Italian regions by taking into account the cardunculus production, no general trend was observed, in fact, as shown in Table 4, a first decrease until 2018 and then an



Figure 1. Study area geographic position.

increase in the cardunculus production was recorded for Umbria, Tuscany and Veneto regions; an increase over the years was registered for the region of Marche, Molise and Lazio, instead of a production decrease was observed for the region of Campania, Sardinia, Liguria and Lombardy, which starts its production from 2018.

Since, as reported in both Tables 3 and 4, related to *Cynara cardunculus L.* cultivation, Sicily is the region with both the highest cultivated area (i.e. 14,955 ha/y) and, above all, the highest production (i.e. 159,721 t/y), it was selected as study area.

2.3. Data analysis

In this study, an extensive database was improved according to statistical sources, i.e. ISTAT (2016–2020), in order to quantify both the Cardunculus cultivation surface areas and its production for evaluating their distribution at territorial level by GIS analyses.

The base maps used in the GIS software included the Regional Technical Maps (RTM 2008) as the base map for carrying out both thematic maps and heatmaps.

By analysing available data on the agricultural sector, i.e. horticultural cultivation, the provinces with the highest surface areas dedicated to Cardunculus cultivation and with the highest amount of its production were identified and localised on GIS software.

In detail, the QGIS software (ver. 3.10.11), an open-source GIS software, was used since it is a decision support tool appropriate for collecting, organising, analysing, and localising

geographical data. QGIS software was used to perform all the GIS analyses; by combining data provided by the base maps, data acquired from the database, and by adopting the Jenks tool available in the QGIS software, several maps were produced.

Firstly, the statistical data base of National Institute of Statistic (ISTAT) was used to acquire data relating to the horticultural cultivations by selecting a five-year time interval (2016–2020).

In detail, data concerning cardunculus cultivation and its production were selected and analysed in order to identify both the trend of surface areas and production. Then, by using spatial analysis GIS tools, the acquired data were elaborated and applied to provide distribution of both cultivation surface areas and cardunculus production within the study area. In detail, a territorial distribution of both surfaces areas and production areas were obtained, by classifying the Sicilian provinces through the application of Jenks tool plug-in, with the aim of maximising the differences among the classes.

A tailored methodology was developed in order to quantify the CW amount suitable as potential reinforcements for bio-composite materials, i.e. cardoon stem fibres.

The next step of the methodology was the computation of the index (*cardoonstem*) for describing the amount of cardoons stems availability by applying the following equation:

$$\text{Cardoonstem} = 40\%CW \quad (1)$$

where

Table 3. Italian cultivated area for horticultural crops and Cardunculus cultivation (ha).

	Cultivated area [ha]					Mean [ha]
	2016	2017	2018	2019	2020	
<i>Abruzzo</i>						
- Horticultural open field crops	18,703	18,708	18,722	18,824	20,350	19,061
- Cardunculus cultivation	426	435	443	434	438	435
<i>Apulia</i>						
- Horticultural open field crops	89,244	88,154	88,019	86,387	89,258	88,212
- Cardunculus cultivation	12,300	12,130	12,170	12,230	11,930	12,152
<i>Basilicata</i>						
- Horticultural open field crops	10,851	10,836	10,824	10,751	11,414	10,935
- Cardunculus cultivation	440	432	430	430	430	432
<i>Calabria</i>						
- Horticultural open field crops	21,012	20,951	20,728	20,420	22,493	21,121
- Cardunculus cultivation	283	316	306	314	317	307
<i>Campania</i>						
- Horticultural open field crops	31,669	31,082	31,244	30,882	32,744	31,524
- Cardunculus cultivation	1,212	1,100	952	888	831	997
<i>Emilia-Romagna</i>						
- Horticultural open field crops	53,012	49,697	49,153	52,326	52,816	51,401
- Cardunculus cultivation	86	84	90	97	93	90
<i>Lazio</i>						
- Horticultural open field crops	19,553	19,808	19,547	20,006	21,597	20,102
- Cardunculus cultivation	975	903	998	988	1,023	977
<i>Liguria</i>						
- Horticultural open field crops	929	917	915	911	1,082	951
- Cardunculus cultivation	103	90	90	90	90	93
<i>Lombardy</i>						
- Horticultural open field crops	15,938	15,495	16,867	16,837	17,233	16,474
- Cardunculus cultivation	0	0	4	20	20	9
<i>Marche</i>						
- Horticultural open field crops	9,240	9,255	9,179	9,074	9,212	9,192
- Cardunculus cultivation	67	68	74	74	74	71
<i>Molise</i>						
- Horticultural open field crops	3,885	483	3,583	5,147	5,176	4,255
- Cardunculus cultivation	100	100	120	120	120	112
<i>Sardinia</i>						
- Horticultural open field crops	20,882	17,780	17,867	15,432	13,719	17,136
- Cardunculus cultivation	12,899	9,223	8,850	7,853	6,821	9,129
<i>Sicily</i>						
- Horticultural open field crops	59,357	58,152	58,806	59,320	67,593	60,646
- Cardunculus cultivation	14,300	15,020	15,010	15,212	15,232	14,955
<i>Tuscany</i>						
- Horticultural open field crops	8,633	7,211	7,257	7,326	7,472	7,580
- Cardunculus cultivation	590	552	603	623	681	610
<i>Veneto</i>						
- Horticultural open field crops	19,977	20,389	18,842	20,420	20,749	20,075
- Cardunculus cultivation	48	18	24	35	52	35
<i>Umbria</i>						
- Horticultural open field crops	1,997	1,725	1,720	1,747	1,818	1,801
- Cardunculus cultivation	9	11	11	11	11	11
<i>Others*</i>						
- Horticultural open field crops	9,543	9,480	9,704	9,454	7,783	9,193
- Cardunculus cultivation	0	0	0	0	0	0

*Piedmont, Friuli-Venezia Giulia, Valle d'Aosta, and Trentino Alto-Adige regions.

CW represents the total amount of wastes, which correspond to about the 80–85% of the artichoke ground biomass (Pandino, Lombardo, and Mauromicale 2013); the 40% is the percentage of stems useful for extracting vegetal fibres (Esposito et al. 2016).

The obtained results were reported in GIS and, by using the Jenks tool, were elaborated for assessing those territorial areas highly characterised by this kind of potential recyclable cellulose-based fibres. Then, with the aim of estimating those areas, within each province, characterised by the highest density of cardoon stems, before applying the Heatmap plugin available in QGIS software, the centroids for each province were computed. Therefore, firstly the Polygon centroid plugin was applied; then, the produced base map was used for carrying

out the heatmap based on the amount of available cardoon stems. In detail, during the Heatmap plugin application, the discrete-interpolation method was set and, in order to increase the influence certain features, have on the resultant heatmap, the input feature was weighted by the attribute related to the stem availability.

Finally, the amount of cardoon stem fibres was combined with that of sheep wool fibres, previously investigated by (Parlato and Porto 2020), in order to highlight the territorial areas with the highest availability of these two different cellulose and protein-based fibres, both suitable for new eco-friendly materials. The selected areas could be useful for localising future collection centres by reducing environmental impact due to the logistic and supply phase.

Table 4. Italian production of horticultural crops and Cardunculus cultivation (t).

	Production [t]					Mean [t]
	2016	2017	2018	2019	2020	
<i>Abruzzo</i>						
– Horticultural open field crops	600,961	580,207	580,723	582,401	639,681	596,795
– Cardunculus cultivation	5,863	5,930	6,017	5,995	6,069	5,975
<i>Apulia</i>						
– Horticultural open field crops	3,195,168	3,035,745	2,987,559	2,936,851	3,047,654	3,040,595
– Cardunculus cultivation	114,325	121,260	128,550	129,950	124,540	123,725
<i>Basilicata</i>						
– Horticultural open field crops	317,350	312,455	311,101	310,157	342,614	318,735
– Cardunculus cultivation	5,316	5,295	5,262	5,262	5,262	5,279
<i>Calabria</i>						
– Horticultural open field crops	559,711	523,260	539,175	534,706	589,038	549,178
– Cardunculus cultivation	3,165	3,289	2,996	3,055	3,068	3,115
<i>Campania</i>						
– Horticultural open field crops	986,350	919,706	924,991	945,628	1,009,690	957,273
– Cardunculus cultivation	21,196	18,492	16,439	14,921	13,639	16,937
<i>Emilia-Romagna</i>						
– Horticultural open field crops	2,677,720	2,434,889	2,271,514	2,252,276	2,556,738	2,438,627
– Cardunculus cultivation	362	409	304	479	521	415
<i>Lazio</i>						
– Horticultural open field crops	572,592	609,251	665,188	695,556	766,602	661,838
– Cardunculus cultivation	12,540	12,230	22,055	22,570	23,050	18,489
<i>Liguria</i>						
– Horticultural open field crops	20,222	19,416	18,300	18,073	18,697	18,942
– Cardunculus cultivation	1,076	930	930	930	936	960
<i>Lombardy</i>						
– Horticultural open field crops	773,837	760,250	763,684	719,307	891,936	781,803
– Cardunculus cultivation	0	0	32	108	104	49
<i>Marche</i>						
– Horticultural open field crops	124,013	121,682	122,231	117,012	125,226	122,033
– Cardunculus cultivation	284	365	431	443	443	393
<i>Molise</i>						
– Horticultural open field crops	95,987	107,031	118,563	168,128	167,994	131,541
– Cardunculus cultivation	1,210	1,350	1,800	1,800	1,440	1,520
<i>Sardinia</i>						
– Horticultural open field crops	322,568	306,620	321,141	284,843	258,084	298,651
– Cardunculus cultivation	72,047	49,952	48,852	45,944	38,107	50,980
<i>Sicily</i>						
– Horticultural open field crops	954,415	967,496	954,268	950,530	1,115,498	988,441
– Cardunculus cultivation	147,390	178,660	165,935	152,910	153,711	159,721
<i>Tuscany</i>						
– Horticultural open field crops	261,175	211,488	215,989	195,634	203,912	217,640
– Cardunculus cultivation	4,437	4,148	2,894	3,073	4,747	3,860
<i>Veneto</i>						
– Horticultural open field crops	480,271	524,484	425,016	461,406	567,999	491,835
– Cardunculus cultivation	360	135	180	280	414	274
<i>Umbria</i>						
– Horticultural open field crops	47,810	33,148	34,734	36,491	37,175	37,872
– Cardunculus cultivation	53	55	23	59	59	50
<i>Others*</i>						
– Horticultural open field crops	246,633	244,164	246,073	330,330	296,013	272,643
– Cardunculus cultivation	0	0	0	0	0	0

*Piedmont, Friuli-Venezia Giulia, Valle d'Aosta, and Trentino Alto-Adige regions.

3. Results and discussion

Data recorded from ISTAT database (2016–2020-time interval) were elaborated and deeply analysed in order to consider only data related to Cardunculus cultivation and production. Data were organised to show at territorial level the distribution of this cultivation within Sicilian provinces by developing a GIS map.

As first step, the acquired data were used for providing the distribution of cultivated areas dedicated to cardunculus production, by showing them at territorial level. Then, by using Jenks tool, available in QGIS software, the Sicilian provinces were grouped in three different classes based on their

cardunculus cultivated areas. As shown in [Figure 2](#) Caltanissetta province, followed by Agrigento and Catania are those ones with the main surface area dedicated to the Cardunculus cultivation.

In detail respectively, about an average of 6000, 4000 and 2000 ha of surface area are yearly cultivated, which correspond to about the 80% of the total cardunculus cultivated surface area in Sicily.

Since the areas with the highest surface of cultivated area do not always correspond to those with the highest production, the cardunculus production was analysed by considering averaged data belonging to the same time interval (2016–2020).

As reported in Figure 3, the results of the elaborations showed a different distribution within Sicilian provinces and confirmed Caltanissetta and Agrigento as most productive provinces, with about 47,000 tons and 42,400 tons of yearly production, respectively, which correspond to 60% of the total Sicilian production.

Furthermore, the distribution of the cultivated areas allows the identification of the highly representative area for this cultivation located in the south of the Island.

Since the research paper was focused on estimating the amount and localisation of cellulose-based fibres that could be reuse as potential reinforcements for bio-composite materials, i.e. cardunculus fibre, firstly among the cardunculus production only the cardoon stems, which represent, on average, about 40% of total cardoon waste were considered with the aim of quantifying the available cellulose-based fibres.

Therefore, by applying Equation 1, data related on the available cardoon stems were obtained and reported on GIS map (Figure 4).

Data shown in Figure 4 confirms the provinces of Caltanissetta and Agrigento as those ones with the highest availability of potential recyclable cellulose-based fibres, i.e. cardoon stems, with about 15,000 and 13,000 ton/y of produced cardoon stems, respectively.

With the aim of producing a tailored heatmap based on the computed amount of cardoon stems firstly, the polygon centroids were computed (Figure 5a) and applied for developing the heatmap (Figure 5b).

The heatmap results, as reported in Figure 5b, highlighted two big areas where cardoon stems are highly concentrated, i.e. the central area and southeast one. In this regard, the provinces

of Caltanissetta, Agrigento, Ragusa and Catania are the provinces where more than 4000 tons/year of cardoon stems are yearly available.

The results reported in Figure 5b concerning the amount and location of cardoon stem fibres, recyclable as potential reinforcements for bio-composite materials, are essential for a better management of collection centres by considering the existing infrastructures in order to optimise the collection process and therefore reduce CO₂ emissions that is the major responsible for the global warming.

The use of these fibres in Sicily, where the cardunculus production is huge, can produce important benefits in terms of new jobs (i.e. green jobs) in a region with high unemployment (Fiore, Valenza, and Di Bella 2011).

Since, as reported by several authors in literature, (Picuno, 2016; Wang et al. 2018; Parlato and Porto 2020), a sustainable building process could be improved by using natural insulation materials instead of those commonly used (e.g. polyurethane foam, polystyrene (EPS), fibreglass, mineral wool), and cellulose and protein-based fibres, i.e. fibre extracted by cardoon stems and sheep wool fibre (Galan-Marín, Rivera-Gomez, and Garcia-Martinez 2016), as reinforcements for bio-composite materials instead of synthetic ones. In this context, several research studies successfully demonstrated the possibility of using sheep wool fibres, not only as natural insulation material (Parlato and Porto 2020), but also within different composite matrices, such as unfired clay adobe or cement mortar (Galán-Marín, Rivera-Gómez, and Petric-Gray 2010a; Galán-Marín, Rivera-Gómez, and Petric-Gray, 2010b; Mounir et al. 2015).

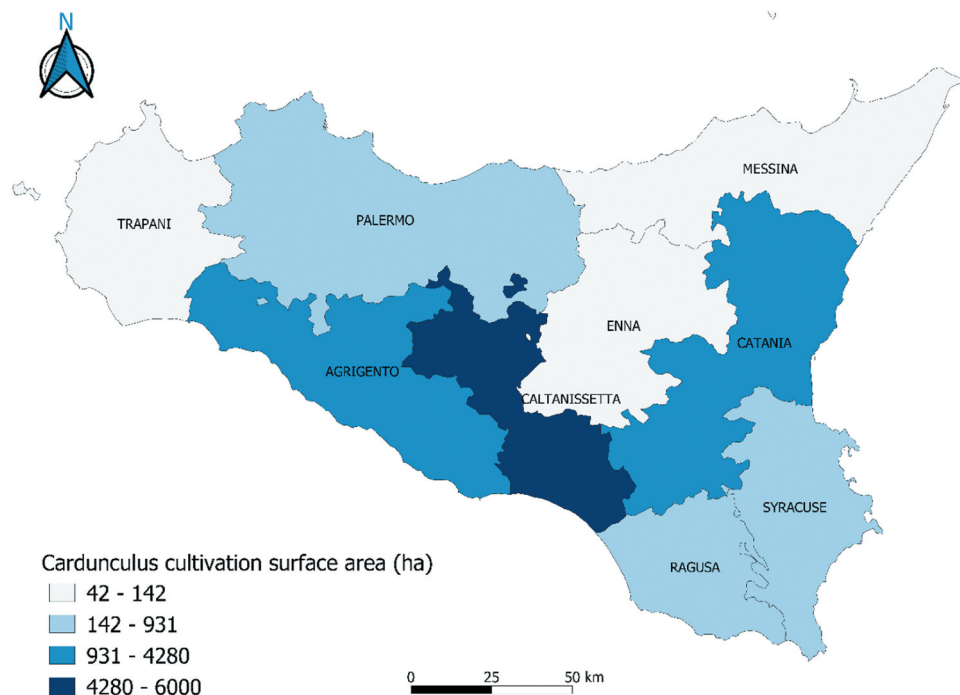


Figure 2. Distribution of cardunculus cultivated surface area within the Sicily region.

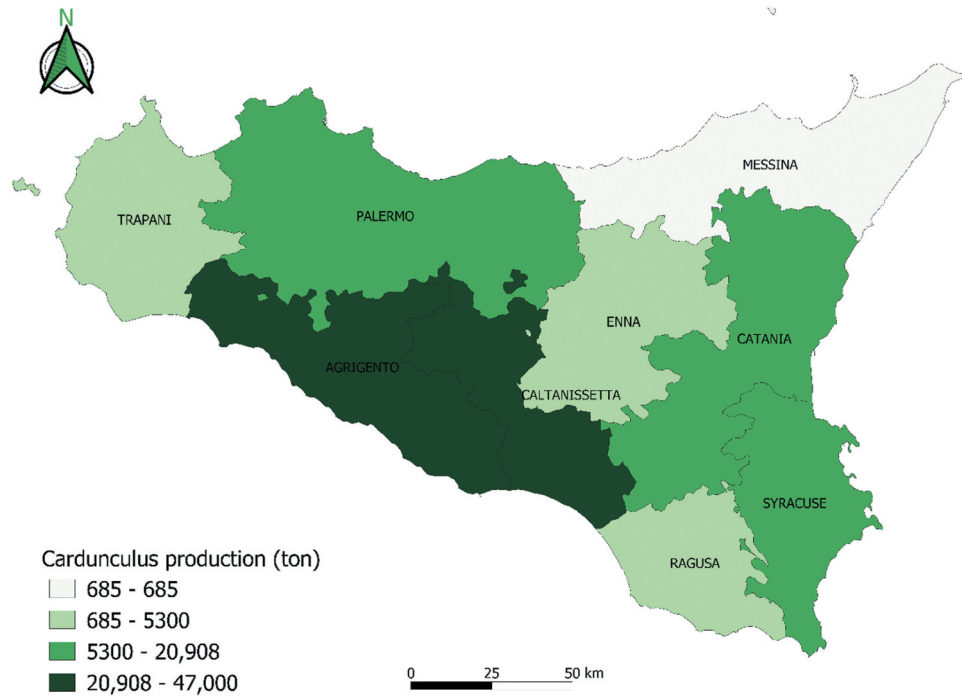


Figure 3. Cardunculus production distribution within Sicily region.

Furthermore, as reported by (Parlato and Porto 2020), Sicily is the second region in Italy for number of sheep, with more than 900,000 heads that correspond to about an annual production of almost 1,000 tons of greasy wool (nowadays considered a special waste). In this context, data related to the quantity of sheep wool as recyclable fibres were elaborated and reported in GIS. Firstly, in order to show at territorial level, the distribution of those areas where sheep wool is highly available, by taking

into account the number of Sicilian sheep, the amount of sheep wool was quantified and reported in GIS. Figure 6 shows at a territorial level the distribution of the computed available sheep wool, by highlighting the inner area of the Island as the most suitable for this kind of by-products.

By overlying results reported in Figure 6 related to sheep wool availability areas, with those reported in Figure 4, related instead to the cardoon stems distribution,

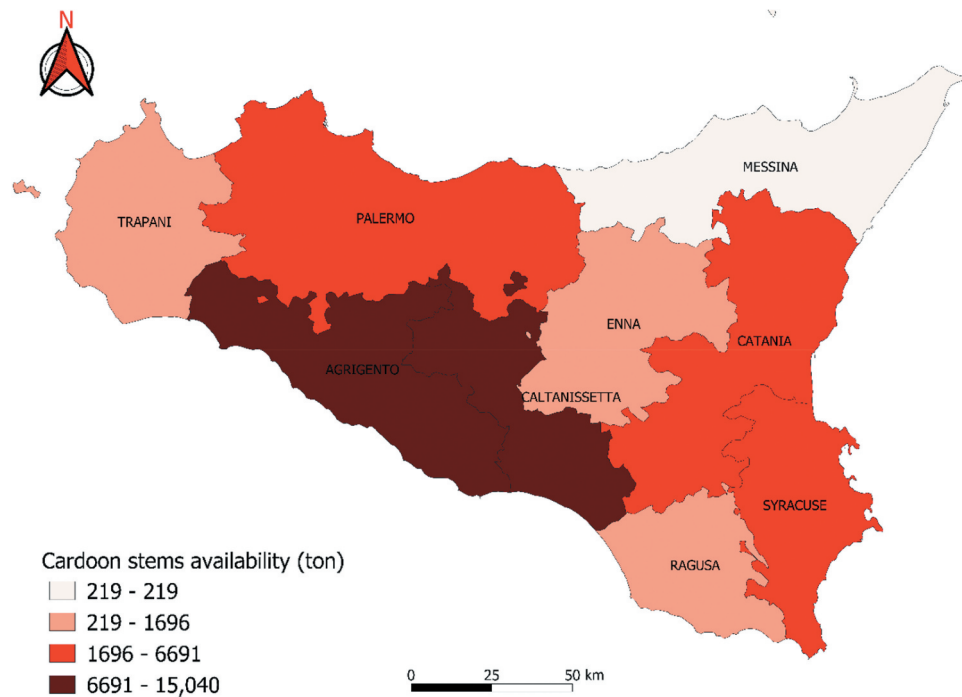


Figure 4. Available cardoon stems distribution within Sicily region.

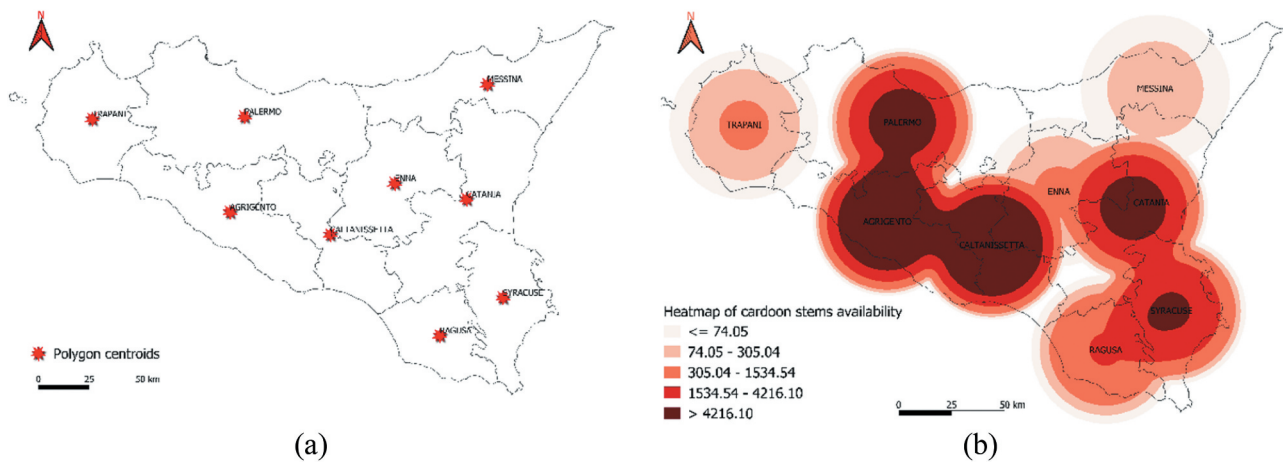


Figure 5. Cardoon stems distribution. (a) Polygon centroid for developing heatmaps. (b) Heatmap distribution based on the computed cardoon stem production.

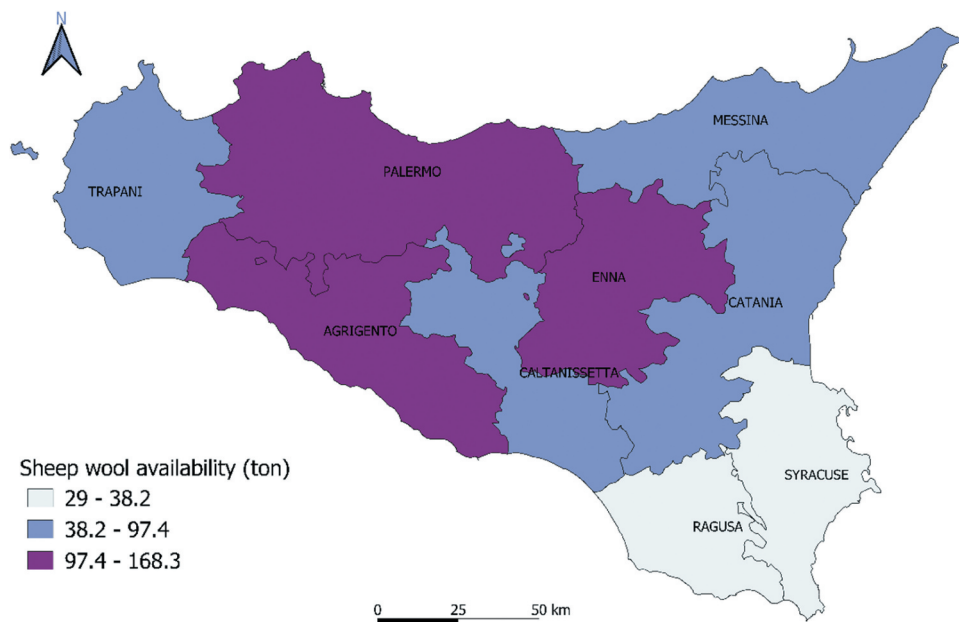


Figure 6. Distribution within Sicily region of the recyclable sheep wool protein-based fibres as potentially reinforcements for bio-composite material.

a map was produced in order to define the most representative area by combining these two cellulose and protein-based fibres (Figure 7).

From Figure 7 the provinces of Caltanissetta and Agrigento resulted as the most proper for locating collection centres due to the high concentration of both the considered fibres.

Therefore, in view of obtaining new eco-friendly materials, by using fibres from both cardoon stems and sheep wool and with the aim of reducing the transport cost for transferring them to the recycling plants (Díaz-Palacios-Sisternes, Ayuga, and García 2014; Osmani and Zhang 2017), the optimisation of the location of new collection centres is required. In this context, the results obtained in this study by developing the GIS-based model could represent a first step to achieve the objective and could be also used to plan in detail the location of such collection centre by using the developed heatmap (Figure 5).

4. Conclusions

This research study was carried out by combining data recorded from a statistic database (ISTAT) and GIS-based maps, fulfilling the proposed aim of the research. In detail, the horticultural production, by focusing on *Cardunculus* cultivation, was deeply investigated by elaborating the data related to both the cultivation surface area and its production for producing GIS maps. The achieved results by the developed GIS-based model contribute to fill the gap in the knowledge of the production and localisation of cardoon stems as potential reinforcement cellulose and protein-based fibres by its recycling process and to support new eco-building material production. A new industrial chain could be created, which could generate potential source of value to be used and exploited through new production cycles, according to the principles of circular economy.

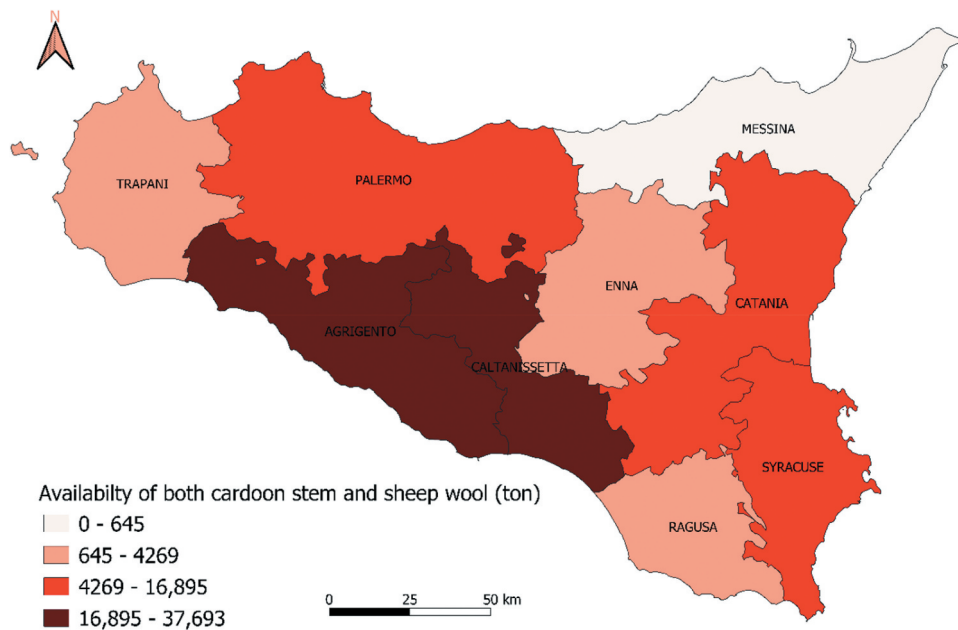


Figure 7. Distribution within Sicily region of both recyclable sheep wool and cardoon stem cellulose-based fibres as potentially reinforcements for bio-composite material.

In this regard, the obtained results could be useful for planning tailored collected centres as near as possible to those areas where these by-products are highly produced. This condition is relevant for a sustainable valorisation by paying attention to the transport costs during the logistics and supply phase (i.e. from the cultivated fields to the collection centres), with an advantage in terms of environmental and social impacts, and costs. Finally, in this study also sheep wool fibre localisation was considered for the same purpose above-mentioned, by highlighting, through the overlay of both (i.e. cardoon stems and sheep wool fibres) the obtained territorial distributions, those areas most suitable for localising collection centres. After the identification of the most suitable areas, the future goal of this research work is to investigate the suitability of the combination of these kind of fibres for new kind of composites by analysing their mechanical properties.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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