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PhD in Agricultural, Food and Environmental Science

XXXIV CYCLE

SUSTAINABLE REUSE OF AGRICULTURAL WASTES FOR ECO-FRIENDLY BUILDING MATERIALS

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Index

Research highlights

- Environmental sustainability
- Circular economy
- Green building
- Agricultural waste reuse
- Land management
- GIS modelling
- Eco-friendly materials
- Raw earth materials
- Natural fibres

Abstract

Nowadays, building sector is the most responsible for environmental degradation, global warming, and climate change with the 50% of carbon emissions, 20–50% of consumption of energy and natural resources, and 50% of total solid wastes production in the world.

Ecological concerns such as environmental safety, energy efficiency and saving, and recyclability and reuse of wastes, have resulted in an increasing interest in new alternatives materials derived from renewable resources. Several studies are focused on new resources and sustainable materials that could be involved and integrated into building process with the aim of replacing traditional building materials, e.g., concrete, steel, plastic components; eco-friendly materials are fully recyclable, sustainable, non-toxic for human and animal health, with a low carbon foot and generally obtained by using natural and renewable sources. Totally in accordance with the circular economy statements, eco-building materials could be also obtained by the reconversion of wastes, e.g., solid wastes coming from urbanized area and agricultural wastes.

Each year in the world the agricultural wastes (AW) production increases at an average rate of 5% to 10 %. The AW unplanned reuse represents a big issue for environment pollution protection, i.e., soil contamination and air pollution, and rural landscape degradation. Moreover, a not properly AW disposal management of also results in a waste of many valuable biomass resources.

In the last years, the valorization of AW is become an important step for environmental protection, energy saving and sustainable development.

The effective transformation and re-utilization of agricultural waste is affected by lags of agricultural automation, and by the large quantity, mostly unknown, and distribution at territorial level of agricultural wastes; these aspects result in an inadequate strategy and policy of disposal management and recycling process.

This PhD research project stems from the need to exploit wastes or by-products materials deriving from agricultural processes, and their potential reuse in the building sector for renovation or new construction materials. The aim was to evaluate the potential use of some agricultural wastes, i.e., plastic films, sheep wool fibers,

cardoons stem fibers, to improve the agriculture building's sustainability and their energy efficiency.

By turning them into a resource for manufacturing new products (e.g., plastic granules, natural reinforcement fibers, insulating elements), a dual purpose could be achieved by obtaining benefit for farmers with a disposal wastes cost reduction, and by improving environmental protection.

Since a waste could become a resource when it is available and easily accessible, to evaluate the availability of these wastes the first step was to analyze their amount and spatial distribution at a territorial level, by using a Geographical Information Systems (GIS) model. Then, by considering sheep wool fiber, an experimental trial was developed in order to evaluate its physical and mechanical properties and its effects of reinforcement fiber on raw earth materials behaviors. At the end, the estimated available cardoon stems yearly amount was combined with sheep wool fiber yearly amount and reported in a GIS map with the aim of obtaining basic information needed to define suitable location for waste collection centers in the analyzed study area.

The GIS-based model results provided key information for a correct disposal management and for the analysis of the environmental impact related to the logistics and supply phase due to the transportation of the estimated amount wastes to future collection centers.

Definitely, to close a material's production cycle, by using it from *the cradle to the cradle,* it's the only possible way to reduce global warming and CO_2 emissions in the atmosphere, changing an ever-growing and unsustainable production process that characterized the modern society.

Riassunto

Al giorno d'oggi l'industria delle costruzioni, con il 50% delle emissioni di anidride carbonica, fra il 20% e il 50 % di consumo di risorse energetiche e naturali, e con il 50% della produzione di rifiuti solidi, è considerata a livello mondiale la principale responsabile del degrado ambientale, del riscaldamento globale e dei cambiamenti climatici.

Aspetti come la salvaguardia ambientale, il risparmio e l'efficienza energetica, il riciclo e valorizzazione degli scarti, hanno determinato un aumento di interesse verso nuovi materiali alternativi ottenibili da risorse rinnovabili.

Molti sono gli studi focalizzati sull'utilizzo di nuove risorse e materiali sostenibili che possono essere integrati nei processi di costruzione al fine di sostituire i materiali tradizionali come per esempio il cemento, l'acciaio e i materiali plastici.

I materiali eco sostenibili sono generalmente totalmente riciclabili, non tossici per la salute umana e animale, con una bassa impronta energetica e ottenuti dall'utilizzo di risorse naturali e rinnovabili.

In completo accordo con i requisiti dell'economia circolare, tali materiali possono anche essere ottenuti dalla valorizzazione, mediante recupero e riconversione, dei rifiuti, sia per esempio solidi urbani che derivanti dai processi di produzione agricola.

In particolare, la produzione degli scarti agricoli aumenta in media ogni anno di una quantità compresa fra il 5% e il 10%. Il non riutilizzo di tali scarti rappresenta un grande problema in termini di inquinamento e degrado ambientale, soprattutto riguardo la contaminazione dei suoli, inquinamento delle falde e deterioramento del paesaggio rurale.

Inoltre, una non appropriata gestione degli scarti determina anche uno spreco di risorse quali grandi quantità di biomasse.

Negli ultimi anni la valorizzazione degli scarti agricoli è diventato un importante *step* per la protezione ambientale, la salvaguardia energetica e lo sviluppo sostenibile.

Tuttavia, l'effettiva trasformazione e il riuso di tali scarti sono in parte compromessi da una mancanza di automazione ed innovazioni in campo agricolo, ma soprattutto dalla mancanza di adeguate informazioni sulla quantità e la localizzazione a livello territoriale che comportano un'inadeguata gestione dei rifiuti e del processo di riciclo.

Il mio progetto di dottorato di ricerca nasce dall'esigenza di investigare sul potenziale riuso degli scarti e dei sottoprodotti agricoli nel campo delle costruzioni sia per il restauro che per la realizzazione di nuove costruzioni, soprattutto rurali.

Lo scopo è stato quello di valutare il potenziale riutilizzo di alcuni scarti agricoli, come film plastici utilizzati per la copertura delle serre, fibre di lana di pecora e fibre ottenibili dagli steli del carciofo, col fine di migliorare la sostenibilità e l'efficienza energetica dei fabbricati rurali.

La conversione degli scarti derivanti da produzioni agricole per la realizzazione di nuovi componenti da utilizzare nella bioedilizia, come per esempio granuli plastici, fibre naturali di rinforzo per materiali bio-compositi, o per materiali termo isolanti, consente il raggiungimento di un doppio beneficio, infatti da una parte si ottiene un beneficio per gli agricoltori che vedrebbero ridotti gli oneri e costi relativi allo smaltimento di rifiuti alle volte considerati "speciali" che diventerebbero anzi un bene di scambio, e al contempo si attuerebbe un sistema di salvaguardia e prevenzione dell'ambiente dai danni inerenti il loro smaltimento, lecito e non.

Poiché uno scarto può essere considerato risorsa nel momento in cui esso è disponibile e facilmente reperibile, il primo passo di questo studio è stato quello di valutare la disponibilità degli scarti oggetto di studio. Mediante l'utilizzo di una metodologia "*Geographical Information Systems"* (GIS), è stata analizzata e valutata la loro disponibilità, anche in termini di volumi, e la loro distribuzione nel territorio, nelle diverse aree di studio considerate.

Successivamente, dopo aver effettuato una accurata campagna sperimentale riguardante la caratterizzazione fisica e meccanica delle fibre di lana di pecora, sono stati eseguiti una serie di test meccanici, termici e fisici che hanno permesso di valutare l'utilizzo di tale fibra come fibra di rinforzo per elementi costruttivi in terra cruda. Infine, si è presa in considerazione la fibra ottenibile dagli steli del carciofo. Anche in questo caso, tramite un modello GIS che ha permesso la realizzazione di mappe tematiche, è stata valutata ed analizzata la disponibilità di tale fibra che è stata in ultima analisi confrontata con la distribuzione e la produzione annua delle fibre di lana.

L'utilizzo di modelli GIS consente di ottenere informazioni fondamentali per una corretta gestione dei rifiuti e per determinare la più idonea localizzazione per futuri centri di raccolta di tali scarti, potendone anche considerare l’impatto, dal punto di vista logistico e non, sul territorio.

La chiusura del ciclo di produzione di un qualunque materiale, dalla culla alla culla (parafrasando una frase celebre) rappresenta l’unica via possibile per ridurre il riscaldamento globale, le emissioni di CO_2, invertendo la rotta di un processo di produzione irreversibile e non sostenibile.

1 Introduction

1.1 Prefaces

Since 1880, when humans began to regularly register temperatures, the global average temperatures have increased by 1.2 degrees Celsius with the greatest global warming trend occurring in the 20th century. In recent geologic history, this warming is dramatically abnormal, and measurements collected over the last six decades by oceanographic researchers show that also every layer of the ocean is warming up.

The climate crisis has become progressively evident, as revealed by repeated recordings of extreme heat events in the summer or too low winter temperatures, and by the melting of glaciers and polar ice. Moreover, as the planet warms, events such as forest fires in Siberia, Sweden, and Australia are becoming more frequent (in the summer 2021 an enormous wildfires burned across Siberia larger than all the fires around the world combined in the same period (Leskinen et al. 2020)

Several researchers are studying the climate changes to understand the factors that cause the global warming (Hamza et al. 2020). They identified that the main factors are variations in solar energy, ocean flow, volcanic activity, and the increase of greenhouse gases in the atmosphere; all these factors are caused preliminary by humans' activities that determine the growth of atmospheric concentrations of carbon dioxide (CO_2) (AINSWORTH 2008; Kalhapure et al. 2019; North 2014). In the last 800 years and before the Industrial Revolution, atmospheric CO_2 concentrations oscillated between 180 parts per million (ppm) and 280 (ppm). Currently, CO_2 level reached the highest never registered values up to 420 (ppm) (Lindsey 2020). Since the Industrial Revolution, fossil fuels are burned to produce energy. During the burning process fossil fuels release greenhouses gas in the atmosphere and this cause the rising of CO_2 concentrations. CO_2 plays a main role in global warming because it is a greenhouse gas that absorbs and radiates heat.

Since 1992, when a climate change strategy was adopted for the first time, the European Union (EU) has a leading role in climate change strategies and policy that are still today considered a priority also by considering the growing evidence of the climate crisis. In 2005, the EU issued the greenhouse gas Emissions Trading Scheme (ETS) and flagship, that represents the most important trading scheme of the EU's climate policy (Bailey 2010).

In 2015 the Paris Climate Agreement established to keep the global warming below 1.5 or 2.0 °C, i.e., at the level of the preindustrial times (Delbeke et al. 2019). To achieve this goal, governments must spend their efforts on both reducing greenhouse gas (GHG) emission and increasing investments for improving energy efficiency and renewable energy.

In 2019 the European Commission, to pursue climate actions in a challenging international setting, issued the 'European Green Deal', i.e., the new agenda for sustainable growth of the European concerning climate policies and measures to be implemented by governments (European Commission 2019).

European Green Deal provides an initial framework of the necessary climate key policies and strategies with the aim to improve a competitive resource-efficient economy. The most ambitious and challenging purpose set out by the Green Deal is to achieve no net greenhouse gases emissions by 2050 (Siddi 2020).

Green Deal success depends on the prioritization of the climate agenda in the European's financial programs of the government involved. Unfortunately, Covid-19 emergency and the related economic crisis affected the realization of the Green Deal Agenda. After the pandemic emergency should be essential to restart the European economy keeping the climate challenges as a priority.

In addition to Green Deal, in 2020 the European Commission adopted a Circular Economy Action Plan (CEAP) based on actions to improve Europe's transition from a linear economy towards a circular one (European Commission 2020).This plan perfectly fits the main Global policies of environmental sustainability that are addressed to promote a sustainable economic growing. CEAP is regarding activities covering the whole economic cycle, starting from the production process until a correct waste management, by implementing actions for the market of secondary raw materials and a revised waste legislative concerning their correct disposal management and their potential re-use.

The building sector is the major contributor to global environmental impacts as well as energy consumption and it is evident that environmental impacts of buildings need to be reduced significantly. In Europe, the energy used in building industry is responsible for up to 50% of CO_2 emissions and consumes up to 40% of all raw materials extracted from the lithosphere (Bonoli, Zanni, and Serrano-Bernardo 2021). In this context, the interest for environmental sustainability, energy efficiency of constructions, generally known as ‘Green Buildings’, it is strongly increasing (Li et al. 2021; Zuo and Zhao 2014). Procedures adopted for Green Buildings are often based on both the reduction of environmental impact of buildings and the improvement of human and animal wellness.

Sustainability and energy efficiency of buildings are based on thermal insulation qualities, energy consumption, and on CO_2 emissions reduction, the use of alternative eco-friendly materials, recyclable, renewable with a low footprint impact, could contribute to achieve a sustainable building sector.

Also in the building sector, the re-use of wastes could be of relevant importance in the circular economy framework, which is one of the main building blocks of the European Green Deal.

1.2 Agricultural Waste

Agricultural wastes, co and by-products are all the residues resulting from agricultural activities, including cultivations, livestock productions and aquaculture. They can be liquids, slurries, or solids and their composition varies according to the type of agricultural activity from which they are generated. Agricultural wastes (AW) include animal wastes, food process wastes, crops wastes, and hazardous chemical waste. The globally growing agricultural production resulted in a significant increase in agricultural wastes; it is estimated that about 998 million tons of agricultural waste are worldwide yearly produced (Bories et al. 2009), often accompanied by the intensive farming system development and by the excessive use of chemical fertilizer. This considerable quantity of wastes represents a serious issue for environment pollution, and landscape quality, especially in rural area, with a toxicity potential to air, water, plants, animals and human, (e.g., AW coming from cultivation are often affected from a high quantity of chemical fertilizers, AW deriving from livestock production present a high bacterial load).

The issue concerning the agricultural wastes also pushed the Green Deal for accelerating the transition to a circular economy. In this regard, as reported in the previously paragraph, European Union (EU) promotes a zero-waste economy by 2025 with the ambitious goal to become the first climate-neutral continent by 2050, by achieving a sustainable transition for the environment and the economy (Hamam et al. 2021). The conversion of wastes into new raw materials is a priority for policy makers and the agricultural wastes (AW) can have an interesting role because if valorized and properly managed can be transformed into a resource for new production cycles (Selvaggi et al. 2021). A correct disposal of management and a potential conversion in new raw materials of agricultural waste could reduce pollution and cost production, realizing a circular economy (Liuzzi, Sanarica, and Stefanizzi 2017; F. Obi, Ugwuishiwu, and Nwakaire 2016). Agricultural wastes need to be considered as potential resources and not undesirable and unwanted residues discharged to the environment. A properly AW utilization is based on five different phases related to collection, storage, treatment, transfer, and utilization. All these phases require new technology, attitudes, incentives, new dedicated policies and substantially a new approach to agricultural wastes management with the aim to obtain a reusable waste products and to control the reintroducing of a non- reusable waste products into the environment (F. O. Obi et al. 2016).

1.3 Scopus of the work and methodology

The main aim of this PhD thesis was an exploration of possible re-uses of agricultural wastes for making new sustainable materials to be used for both the construction and renovation of rural buildings. An Italian region highly representative for the relevance of agricultural activities (Sicily) was considered and three different kinds of wastes and by-products were investigated for possible re-uses, i.e., plastic films used for covering greenhouses, sheep wool fibers, and cardoons fibers, because of their high availability and related concerns of their disposal of. In detail, Sicily is the region with the greatest agricultural surface area used for protected cultivation and the second region for number of sheep, after Sardinia, with a production of almost 1,000 tons of yearly raw wool. Moreover, according to statistical sources, i.e., ISTAT (2016 – 2020), Sicily is the first region for production of *Cynara cardunculus* L. with more than 150,000 t/y that represent the 41% of the Italian total production. The 80-85% of the cardoon cultivation are wastes, constituted of leaves and stems that are the 60% and 40% respectively. A cause of these high quantities, each year their disposal represents a matter for farmer.

A first study of this PhD thesis regarded the post-use sustainable management of greenhouses covering films to avoid environmental degradation with serious ecological and economic consequences. Since a sustainable reuse of AW depends on their availability and geographical location, a methodology was put forward to locate and quantify the wastes considered in this research study, i.e., plastic films used for protected crops. By using GIS, land use analyses were carried out in an area with the highest concentration of protected crops in Italy (Ragusa province). A suitable index for computing Agricultural Plastic Wastes (APW) was chosen from literature, modified and adapted to the scope (Blanco et al. 2018). Post-use management considers the execution of different steps for both the disposal and recycling of agricultural plastic covering film, such as: APW localization and quantification, APW collection, APW transport to landfill or recycling industries, APW processing to obtain secondary raw material (e.g., plastic granules) (Cascone et al. 2020). Currently, more than 85% of plastic wastes ends up in landfills and plastic pollution is one of the biggest environmental concerns due plastic long-life (plastic can take hundreds or thousands of years to be decomposed). In all the production sectors, including agricultural activities, the use of plastic materials is increasing. Each year in the world the consumption of agricultural plastic materials is around 6,5 million tons and more than 1 million tons in Europe (Scarascia-Mugnozza, Sica, and Russo 2012). Among agricultural plastic materials, plastic films used for covering protected crops or for mulching soil are representing the higher amounts.

A second part of this PhD thesis concerning the possible re-use of sheep wool, an agricultural waste produced by breeder. Wool is a renewable, recyclable and environmentally friendly material. On the other hand, sheep wool is a special waste for its potential bacterial load, with high disposal costs for breeder because it should be landfilled for a correct disposal.

The reuse of greasy wool could reduce both environmental pollution and energy consumption by providing a new material fully complying with ecofriendly construction criteria. In fact, sheep wool thanks to its thermo-physical and mechanical behaviors could be suitable for being used as both insulating building materials and reinforcement fibers in bio composites materials, e.g., raw earth adobes, panels or blocks (Donkor and Obonyo 2015; Klarić et al. 2020; Korjenic et al. 2015; Stapulionienė, Vaitkus, and Vėjelis 2017). In first part of the study, by using data supplied by National Zootechnical Registry, a dedicated GIS was developed to localize and quantify sheep and breeder's sheep in Sicily. In this part of the research data collection was carried out for planning tailored collection centers as near as possible to those areas where this kind of waste is highly produced by also analyzing the environmental impact due their localization. Next, a low-quality wool of "*valle del Belice*" sheep highly produced in the area under study, was deeply investigated in order to characterize its mechanical and physical performances in view of a possible application as strengthening system for rammed earth building components. Experimental tests on physical and mechanical behaviours of rammed earth specimens under thermal, flexural and compression tests, were carried out, reported, and discussed. Specimens were realized by adding SWF to a clayey soil. Since mechanical and thermal behaviours of based raw earth - building-components are sensitive to both soil composition and fibre addition, SWF length and percentage were changed to evaluate the most performant mix design.

The third study of this PhD thesis regarded an agricultural waste coming from *Cynara cardunculus* L. (CW) cultivation and its yearly amount. Among natural fibres, due to its mechanical behaviour, *Cynara cardunculus* L. fibre (CW) is well suited as reinforcement for adobe clay or cement mix to building applications. Previously studies, with the aim of evaluate its potential use as reinforcements for polymer composites, carried out an experimental trial for the identification of microstructure, chemical composition and mechanical properties of cardoon stem fibres (Fiore, Valenza, and Di Bella 2011).

To locate and quantify the yearly amount of *Cynara cardunculus* L. waste a GIS - based model was put forward and was applied in a study area located in Southern Italy, which is highly characterized by this horticultural cultivation. Obtained results by the computation of CW amount were adopted and applied in GIS for developing tailored heatmaps that show at territorial level the distribution of the available cardoon stems fibers recyclable as potential reinforcements for bio-composite materials. The estimated available cardoon stems yearly amount was combined with sheep wool fiber yearly amount and reported in a GIS map. The GIS-based model results provided basic information for the analysis of the environmental impact related to the logistics and supply phase due to the transportation of the estimated quantity of fibers from both cardoon stems and sheep wool to a future collection center.

In detail, the PhD thesis is constituted by six papers (one review and five original full papers) published or submitted during the PhD course, as per the list reported below:

1. **Covering plastic films in greenhouses system: A GIS-based model to improve post use sustainable management** (Full paper, published on Journal of Environmental Management 263 (2020) 110389)
2. **Organized Framework of Main Possible Applications of Sheep Wool Fibers in Building Components** (Review, Published on Sustainability 2020, 12, 761; doi:10.3390/su12030761)
3. **Raw earth-based building materials: An investigation on mechanical properties of Floridia soil-based adobes** (Full paper, published on Journal of Agricultural Engineering 52(2) June 2021, DOI: 10.4081/jae.2021.1154)
4. **Natural Fibers Reinforcement for Earthen Building Components: Mechanical Performances of a low-Quality Sheep Wool (“Valle del Belice” sheep)** (Full paper, published on Construction and Building materials on April 2022)

5. **Reuse of livestock waste for the reinforcement of rammed-earth materials: investigation on mechanical performances** (Full paper submitted to JAE in April 2022)
6. **Spatial analysis to quantify and localise the residual cardoon stem fibres as potential bio-reinforcements for building materials** (Full paper, published on International Journal of Sustainable Engineering in February 2022)

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2 Covering Plastic Films in Greenhouses System: A GIS-Based Model to Improve Post Use Sustainable Management

(Research article published in Journal of Environmental Management 263 (2020) 110389)

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Abstract

Yearly, in Europe, more than 1 million tons of plastic materials are used in agricultural activities. Among the possible applications, plastic films for protected cultivation practices are highly used worldwide because of the significant advantage deriving from the shortening of the growing period. However, in the absence of a correct policy disposal of plastic films, environmental degradation could take place with serious ecological and economic consequences.

In this study, a geographical information system (GIS) - based model to locate and quantify the yearly amount of agricultural plastic waste (APW) coming from crop-shelter coverage used in greenhouses system was put forward and was applied in a study area located in southern Italy, highly characterized by protected cultivation practices. Firstly, the areas with the highest density of crop shelters were mapped, then a suitable index to determine APW amount was computed and applied to obtain heat maps related to covering plastic films. Finally, sensitivity analyses were carried out by varying thickness, lifetime, and density of the covering films of the greenhouses, located in the considered samples. The index ranged between 976 kg $ha^{-1}yr^{-1}$and, 2,484 kg $ha^{-1}yr^{-1}$.

The results showed that the density of greenhouses and tunnels-greenhouses is still elevated nearby the coastline, highlighting that the guidelines of the territorial plan of the Province of Ragusa concerning the displacement of protected crops from the coast to the internal rural areas were disregarded. Moreover, the GIS-based model results could provide basic information for the analysis of the environmental impact due to transportation of APW. Therefore, these results could offer a suitable tool to improve the correct disposal management of covering plastic films and the related recycle policy.

Keywords: *plastics waste management; land management; sustainability; GIS modelling; spatial index.*

2.1 Introduction

In accordance with the main Global policies of environmental sustainability, in 2015 the European Commission adopted a Circular Economy Action Plan (CEAP) concerning actions to improve Europe's transition from a linear economy towards a circular one as well as to promote a sustainable economic grown.

The European CEAP foresees actions covering the whole economic cycle from the production process to waste management, measure for the market of secondary raw materials and a revised legislative proposal on waste.

The main objective of the revised legislative framework on waste, entered into force in July 2018, is the reduction of waste by improving disposal management, recovery and reuse rate (Directive (EU) 2018/849). This legislative framework is providing a clear and stable policy to improve long-term investment strategies focusing on prevention, reuse and recycling rates.

The conversion of waste into new raw material is an important aspect of increasing resource efficiency and closing the loop in a circular economy framework. In particular, actions on plastic waste are identified by CEAP as priority. Nowadays, plastic pollution is considered one of the biggest environmental concerns due the long-life material (plastic can take hundreds or thousands of years to be decomposed) and because more than 85% of plastic waste ends up in landfills. Yearly, in Europe about 26 million tons of plastic waste are generated and their recycling rate is less 30%, a great loss for both economy and environment. Worldwide, as it occurs in other production sectors, also for agricultural activities the use of plastic materials being increasing too. Each year, the world consumption of agricultural plastic materials is about 6,5 million tons (Scarascia-Mugnozza et al. 2012) and more than 1 million tons in Europe. A large amount of this plastic material is plastic film for covering protected crops or mulching soil, the rest is used for irrigation piping, packaging, and containers for fertilizers.

Since 1950's the use of plastic films as covering materials for greenhouses developed quickly and it is still growing. Currently protected cultivations are increasing worldwide with about 1,600,000 ha of greenhouses and walk-in tunnels (Espí et al. 2006) of which 405,000 ha are greenhouses widespread in Europe, (mainly in Spain, Italy and France). In Europe, Almeria, in the south of Spain, is the region with the greatest concentration of greenhouses in the world, it is known as the 'Sea of Plastic' (Aguilar M. et al, 2016).

Plastic covering films shorten the growing period, defend crops from environmental risks, such as bad weather conditions, birds and parasites, and create microclimate favorable to plant growth (Ahemd, Al-Faraj, and Abdel-Ghany 2016; Demetres Briassoulis et al. 2013; Kyrikou and Briassoulis 2007).

On the other hand, the increased diffusion of protected crops generates a large amount of agricultural plastic waste (APW) that requires a properly collection, disposal and recycling process. Among the different types of APW collected and directed for recycling, a huge amount is constituted by plastic films used to cover greenhouses, mainly represented by low density polyethylene (LDPE), ethylene vinyl acetate (EVA), polypropylene (PP) or polyethylene (PE).

In 2011 the APW recovering rate in Europe was around 46% and the mechanical recycling rate was about 23% (European commission (DGE) 2011). In some geographical areas, where recovery and reuse processes for plastic wastes are not foreseen, plastic films are left illegally on the margins of cultivated fields, on illegal dumps, or even burned. Their abandonment close to water courses could cause groundwater pollution or an obstacle to the natural flow of water with dramatic consequences such as flooding.

Yearly, in Italy more than 350,000 tons of agricultural plastic materials are used (Picuno et al. 2012) and most of them, that are used as covering films, must be frequently replaced due to their early deterioration caused by exposition to atmospheric agents. For this reason, a correct disposal policy is crucial to avoid environmental pollution.

APW recycling could reduce pollution and prevent economical losses and environmental impacts due to the development of greenhouse cultivation system. In this regard, land conservation policies should include also guidelines for the sustainable management of APW in order to reduce soil and water consumption, soil and aquifers chemical contamination and, organic matter soil decrease (Díaz-Palacios-Sisternes, Ayuga, and García 2014; Picuno, Tortora, and Capobianco 2011; Vox et al. 2016).Therefore, the main aim of this study is to improve post-use sustainable management of greenhouses covering films. Post-use management takes into account the execution of different steps for the disposal or for recycling of agricultural plastic covering film, such as: APW localization and quantification, APW collection, APW transport to landfill or recycling industries, APW processing in order to obtain secondary raw material (e.g., plastic granules).

This research study focused on the first step of post-use management of APW which is crucial in order to put forward a method for a sustainable disposal management and recycling process of APW. Since, Geographic Information System (GIS) tools have been considered as an appropriate platform for environmentally related issues (Valenti et al. 2018) and have been applied for both assessing, quantifying and site-location analysis, in this study a GIS-based model was developed for collecting, organizing, analysing, and visualizing geographical data related to APW. The data coming from the developed model could be adopted by local authorities as input for strategic territorial planning and monitoring.

2.2 *Materials and methods*

2.3 *Case study*

From the analyses of the greenhouses cultivation system in Italy (Table 1), it emerges that Sicily is the region with the greatest percentage and surface of protected cultivation. The spread of the greenhouse cultivation system in Sicily began in the early sixties of the last century thanks to the flexibility and the lightness of plastic films for the covering of crops that allowed the creation of very simple building structures for the production of vegetables. Since the development of protected cultivation took place very quickly, the surface covered by greenhouses between 1960 and 1965 reached about 700 ha from almost insignificant values. The amount of crop shelters in Sicily has been increased progressively during 70^s, and it is still in growth.

Among the Sicilian provinces, Ragusa has the highest concentration of protected crops (Table 2) with a covered surface of about 470,000 ha which is nearly 68% of the regional total and is distributed as follows: 58.7 %, for tomato; 33.6%, for other vegetables; and 6.7% for flowers and ornamental plants (ISTAT, 2010). Therefore, the GIS-based model described in this study was applied to the province of Ragusa (Figure 1).

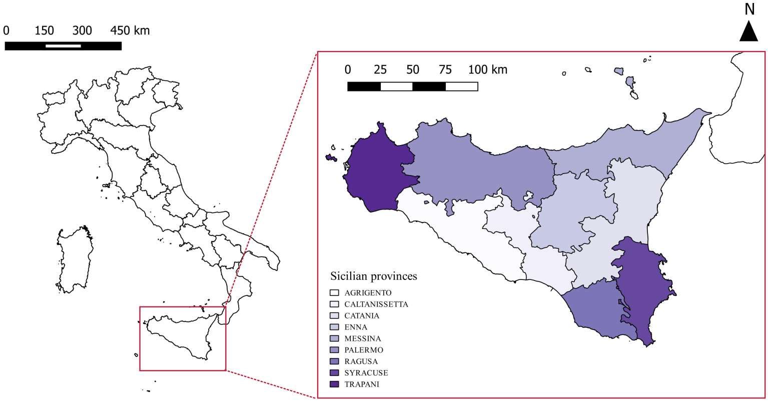

Figure 1 – Italy, Sicily and province of Ragusa

Table 1 – Incidence of greenhouse cultivation system in the Italian regions

Italian regions	Total cultivated surface (TCS) [ha]	Greenhouse surface (GHS) [ha]	[%]
Piedmont	505,090	45,430	9.0
Valle d'Aosta	34,390	130	0.4
Liguria	58,920	58,340	99.0
Lombardy	498,980	72,530	14.5
Trentino Alto Adige	541,410	4,540	0.8
Veneto	551,920	169,530	30.7
Friuli-Venezia Giulia	94,430	5,890	6.2
Emilia-Romagna	783,910	49,700	6.3
Tuscany	846,500	69,650	8.2
Umbria	354,320	5,560	1.6
Marche	366,110	13,490	3.7
Lazio	666,610	312,410	46.9
Abruzzo	481,040	22,590	4.7
Molise	148,730	1,670	1.1
Campania	479,300	355,100	74.1
Apulia	855,850	125,090	14.6
Basilicata	471,100	45,790	9.7
Calabria	507,200	55,740	11.0
Sicily	902,430	686,760	76.1
Sardinia	994,110	64,780	6.5
Total	10,142,330	2,164,700	21.3

The percentage was calculate as [(GHS/TCS)*100]

Table 2 - Greenhouses cultivation areas in the provinces of Sicily (ISTAT 2010)

Province	[ha]
Agrigento	25,410
Caltanissetta	63,868
Catania	11,674
Enna	1,373
Messina	8,241
Palermo	6,867
Ragusa	469,057
Syracuse	81,724
Trapani	18,544
Sicily	686,760

Along the coastal areas of the province of Ragusa, there is a great concentration of tomato cultivation which requires specific features. In detail, tomato, is a warm-season vegetable crop, sensitive to frost and killed by freezing temperatures. To properly growth tomato requires a temperature range between 10°-30°C. Plants do not set fruit when night temperatures are consistently below 10°C and are damaged if temperature exceeds 35 °C. Moreover, this cultivation requires high amounts of potassium and calcium. Tomato crops are rather resistant to salinity and cherry-tomatoes develop a sweeter taste when grown under moderate salinity. In the selected study area, the most widespread typologies of protected crops are tunnel-greenhouses and A-shaped greenhouses. Tunnel-greenhouses are built with a steel bearing structure and are composed of one semi-circular arch or of more joined modules. Its shaped allows accommodating a larger volume of air inside and provides resistance to rain. As regards A-shaped greenhouses, they traditionally are built with wood bearing structure and their basic structural form is the span-type greenhouses, which has a double-sloped roof. Both typologies are covered by plastic films (Figure 2).

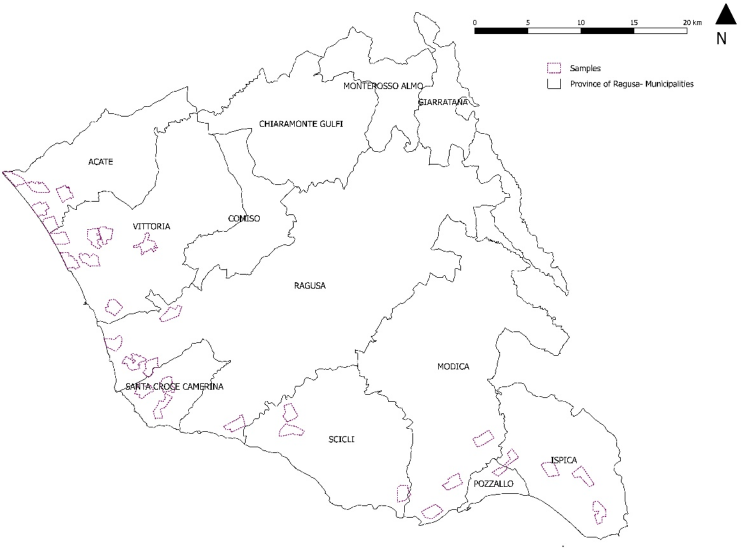

Figure 2 – Location of the thirty samples within the study area

2.4 Agricultural plastic waste (APW) computation

To compute APW, a plastic waste index (PWI) chosen from literature (Lanorte et al. 2017) was adapted, calculated and mapped on a GIS layer.

PWI was calculated by using the following relation:

$$PWI = Scr \times \rho \times TK \times life^{-1} \times Ucvc \; [kg \; ha^{-1} yr^{-1}] \qquad (1)$$

where *Scr* is the surface correction factor; ρ is the plastic film density; TK is the plastic film thickness; *life* is the plastic film useful lifetime; *Ucvc* is the unit conversion factor.

In relation to the different types of both building structures and covering films which characterize the protected crops located in the study area, the index was modified by changing Scr, ρ, TK, $life$.

The surface correction factor *Scr* is used in the equation (1) in order to consider more covering materials than that measured on the plan by aerial top views. It was estimated to be 1.12 (Scr_G) for A-shaped greenhouses and 1.5 (Scr_T) for tunnel-greenhouses. The plastic film density ρ was set to 920 kg m^{-3}or 930 kg m^{-3} in relation to film thickness, i.e., 180 µm or 200 µm. The useful lifetime of plastics film considered was 12 month or 24 months. Finally, the *Ucvc* factor which converts the result in kg ha^{-1} yr^{-1} unit was equal to 0.12.

To obtain the yearly APW estimation, two indices one for A-shaped greenhouses type (PWI_G) and one for tunnel-greenhouses (PWI_T) were multiplied for their covered areas, respectively.

2.5 The GIS-based model for APW computation

In this paragraph, a methodology for investigating the location and quantification of APW film is described. To accomplish this goal, a GIS software tool and statistical tools were used. Literature reports several case studies where APW was mapped and estimated by GIS tools (Blanco et al. 2018; Vox et al. 2016). In some research activities carried out in Spain and in Italy, remote sensing technologies have been used both for greenhouse mapping and for APW evaluation (Aguilar et al. 2016; Arcidiacono and Porto 2010; Lanorte et al. 2017). Other studies compared the results obtained by using GIS-based tool and digital image processing techniques for landscape analysis and for detection of protected cultivation (Arcidiacono and Porto 2008, 2010, 2012; Demetres Briassoulis et al. 2013; D. Briassoulis, Hiskakis, and Babou 2013; Picuno et al. 2011).

In order to explore the spatial distribution of crop shelters in the study area and identify the major contributors to the generation of plastics waste, the GIS-based model was developed by using Quantum GIS (QGIS), a GIS software tool for collecting, organizing, analysing, and visualizing geographical data.

The GIS-based model was implemented by using data collected from base and thematic maps as well as from digital colour orthophotos and farmer interviews. To be more specific, the following data set was used:

- The Regional Technical Map at a scale of 1:10,000, obtained from an aerial flight performed in 2008; it is placed in the zone EPGS:3004, Monte Mario/Italy zone 2 reference system.
- Digital colour orthophotos at a scale of 1:10,000, obtained from an aerial flight performed in 2008; they were placed in the

EPGS:3004, Monte Mario/Italy zone 2 reference system and have a pixel ground resolution of 50 cm.
- Satellite colour images from Google Earth Pro database, which allow the recognition of protected crops in an imagery dated 2017, which is the last available coverage. This image dataset was used in order to analyse the development of the greenhouse coverage in the last 10-year time range.

To compute APW deriving from the plastic covering films the steps reported below were performed:
- Random selection within the Province of Ragusa of thirty area samples suitable for computing the different level of plastic waste production in the whole province of Ragusa. Each sample had an average surface of 150 ha, ranging from 143.81 and 177.3 ha. The number of samples for each municipality was chosen in order to cover about 30% of the whole area covered by protected crops, i.e., A-shaped greenhouses and tunnel-greenhouses.
- Detection and further polygon extraction of protected crops located in each sample, subdivided into two typologies: A-shaped greenhouses or tunnel-greenhouses. This difference was considered because cultivation surfaces covered by tunnel-greenhouses require a greater quantity of plastic films due to the geometry of their bearing structure (Figure 3).
- Implementation of a GIS database with detailed information on covering plastic materials used in the protected crops located in the previous step. The most common covering films used in the study area for protected crops are low density polyethylene films, called LDPE, and ethylene-vinyl acetate copolymer, called EVA. These materials can present different thickness (from 14 µm to 200 µm), different average life (seasonal, when they remain in operation 5-6 months; annual, if they stay outdoors for at least 12-14 months; a long duration, if they remain in place for 24 months or more).

In this study, given the wide heterogeneity found for the covering films detected in each sample, two different thickness (i.e., 180 µm or 200 µm) and two different life durations (i.e., 12 months or 24 months) were considered after having carried out interview to farmers which confirmed their relevant occurrence. Therefore, significant extreme values of 6 months and of 36 months were excluded from the further analyses.

- Computation of the plastic film waste index (PWI) with the equation (1) with the aim of quantifying the yearly production of APW deriving from the two types of protected crops, i.e., A-shaped greenhouses and tunnel-greenhouses. Different values of PWI were estimated and spatially analysed in GIS. Different results were obtained by considering the two analysed typologies of protected crops.
- Basic statistic evaluations to compute the yearly amount of plastic film waste (APW) production for each sample and for each municipality located in the study area.
- Production of thematic maps showing quantity and density of APW, at municipal level.

2.6 Results

Almost all samples were located close to the coast because of the highest concentration of greenhouses in this geographical area (Figure 2)

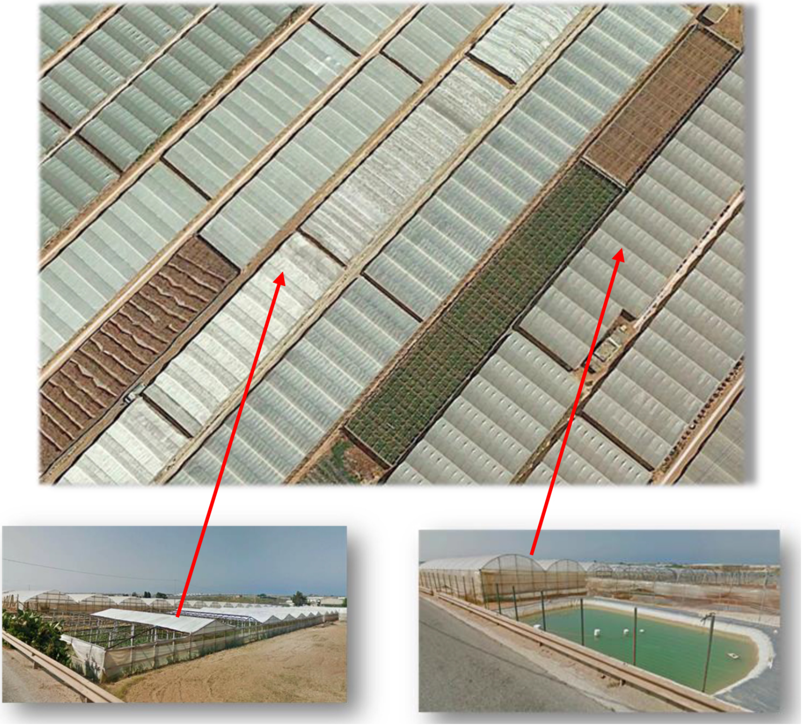

Figure 3 – A-shaped greenhouses and tunnel-greenhouses located in the study area

Within each sample, the classification of protected crops in two different types, i.e., A-shaped greenhouse and tunnel-greenhouses, was carried out by visual analyses of digital colour orthophotos (2012) (Table 3). Among the thirty selected samples, 17 showed a higher number of tunnel-greenhouses type than A-shaped greenhouses one.

Table 3 - Cultivation surfaces covered by tunnel-greenhouses and A-shaped greenhouses within the samples analysed

Sample ID	Surface sample [ha]	T-G area [ha]	G area [ha]	T-G [%]	G [%]
1	148.82	6.16	88.4	4.14	59.4
2	146.79	20.15	76.88	13.73	52.37
3	144.06	45.64	38.81	31.68	26.94
4	143.81	18.14	73.44	12.61	51.07
5	146.44	11.51	38.97	7.86	26.61
6	160.53	23.73	40.73	14.78	25.37
7	154.7	17.42	42.46	11.26	27.45
8	159.12	39.84	31.14	25.04	19.57
9	145.12	36.17	17.27	24.92	11.9
10	158.26	47.39	17.58	29.94	11.11
11	145.62	17.07	5.08	11.72	3.49
12	167.45	29.73	45.03	17.75	26.89
13	177.29	38.18	57.19	21.54	32.26
14	148.54	11.51	59.91	7.75	40.33
15	151.4	13.09	32.88	8.65	21.72
16	157.05	21.15	20.04	13.47	12.76
17	155.16	20.7	16.1	13.34	10.38
18	156.76	14.85	16.48	9.47	10.51
19	143.89	12.59	21.67	8.75	15.06
20	143.38	32.75	47.41	22.84	33.07
21	171.57	24.4	7.9	14.22	4.6
22	149.98	23.84	0	15.9	0
23	149.35	10.33	5.94	6.92	3.98
24	149.33	10.08	5.25	6.75	3.52
25	152.87	33.65	0	22.01	0
26	156.22	8.24	10.03	5.27	6.42
27	146.98	46.32	0.09	31.51	0.06
28	160.05	48.72	2.57	30.44	1.61
29	157.29	12.92	0	8.21	0
30	150.84	19.07	2.08	12.64	1.38

T-G: tunnel – greenhouses; G: A-shaped greenhouses

A preliminary result obtained from the application of the GIS-based model is the heat-map reported in Figure 4, which shows the major concentration of A-shaped greenhouses and tunnel-greenhouses in the study area.

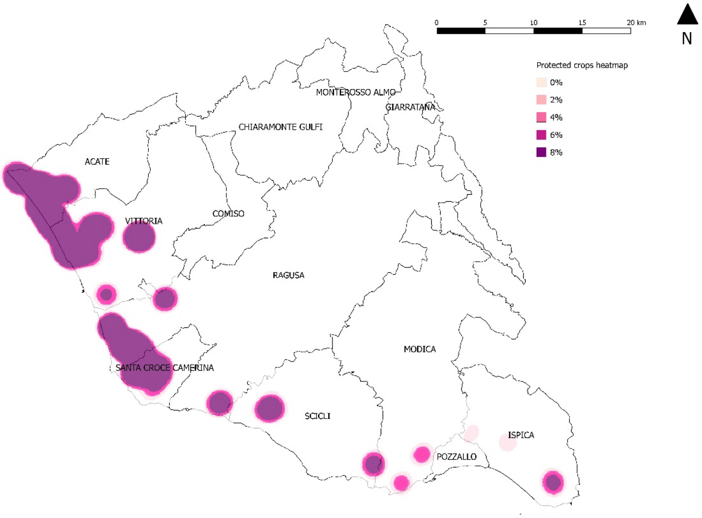

Figure 4-protected crops heat map

For each type of greenhouses, i.e., tunnel-greenhouses and A-shaped greenhouses, four values of PWI were computed by changing thickness and life duration of the covering material (Table 4).

The minimum value of PWI was 976.40 (kg ha^{-1} yr^{-1}) for A-shaped greenhouses type, for a film of 180 μm thickness having a life duration of 24 months. The maximum value of PWI was 2484.00 (kg ha^{-1} yr^{-1}) by considering tunnel-greenhouses type, 200 μm thickness film and a material life duration of 12 months. Mean values and standard deviation were also evaluated as appear in Table 4.

For each territorial sample, the values of PWI_G and PWI_T were computed in order to obtain the yearly amount of plastic waste production (APW kg yr^{-1}) (Table 5).

By comparing the APW values, based on same life duration, a variation of about 11% was observed between 180 μm and 200 μm for both tunnel-greenhouses and A-shaped greenhouses.

Table 4 - Plastic waste index (PWI) computed for tunnel-greenhouses and A-shaped greenhouses

	PWI [kg ha^{-1}yr^{-1}]			
Type	Tunnel-greenhouses		A-shaped Greenhouses	
TK [μm]	180	200	180	200
12 [*month*]	2484.00	2790.00	1854.70	2083.20
24 [*month*]	1242.00	1395.00	976.40	1041.60
Mean	1863.00	2092.00	1415.55	1562.40
SD	878.23	986.41	621.05	736.52

Table 5 - APW evaluation, results obtained by multiplying the four different values of PWI for the corresponding area of protected crops

		Thickness/life duration [μm/month]							
id	Area	180/12	180/24	200/12	200/24	180/12	180/24	200/12	200/24
	[ha]	APW Tunnel-greenhouses [kg yr^{-1}]				APW A-shaped Greenhouse [kg yr^{-1}]			
1	148.82	15301.44	7650.72	17186.40	8593.20	163955.50	86313.76	184154.90	92077.44
2	146.79	50052.60	25026.30	56218.50	28109.25	142589.30	75065.63	160156.40	80078.21
3	144.06	113369.80	56684.88	127335.60	63667.80	71980.91	37894.08	80848.99	40424.5
4	143.81	45059.76	22529.88	50610.60	25305.30	136209.20	71706.82	152990.20	76495.1
5	146.44	28590.84	14295.42	32112.90	16056.45	72277.66	38050.31	81182.30	40591.15
6	160.53	58945.32	29472.66	66206.70	33103.35	75541.93	39768.77	84848.74	42424.37
7	154.7	43271.28	21635.64	48601.80	24300.90	78750.56	41457.94	88452.67	44226.34
8	159.12	98962.56	49481.28	111153.60	55576.80	57755.36	30405.10	64870.85	32435.42
9	145.12	89846.28	44923.14	100914.30	50457.15	32030.67	16862.43	35976.86	17988.43
10	158.26	117716.8	58858.38	132218.10	66109.05	32605.63	17165.11	36622.66	18311.33
11	145.62	42401.88	21200.94	47625.30	23812.65	9421.87	4960.112	10582.66	5291.32
12	167.45	73849.32	36924.66	82946.70	41473.35	83517.14	43967.29	93806.50	46903.25
13	177.29	94839.12	47419.56	106522.20	53261.10	106070.30	55840.32	119138.20	59569.10
14	148.54	28590.84	14295.42	32112.90	16056.45	111115.10	58496.12	124804.50	62402.26
15	151.4	32515.56	16257.78	36521.10	18260.55	60982.54	32104.03	68495.62	34247.81
16	157.05	52536.6	26268.30	59008.50	29504.25	37168.19	19567.06	41747.33	20873.66
17	155.16	51418.80	25709.40	57753.00	28876.5	29860.67	15720.04	33539.52	16769.76
18	156.76	36887.40	18443.70	41431.50	20715.75	30565.46	16091.07	34331.14	17165.57
19	143.89	31273.56	15636.78	35126.10	17563.05	40191.35	21158.59	45142.94	22571.47
20	143.38	81351.00	40675.50	91372.50	45686.25	87931.33	46291.12	98764.51	49382.26
21	171.57	60609.60	30304.80	68076.00	34038.00	14652.13	7713.56	16457.28	8228.64
22	149.98	59218.56	29609.28	66513.60	33256.80	0	0	0	0
23	149.35	25659.72	12829.86	28820.70	14410.35	11016.92	5799.81	12374.21	6187.10
24	149.33	25038.72	12519.36	28123.20	14061.60	9737.17	5126.10	10936.80	5468.40
25	152.87	83586.60	41793.30	93883.50	46941.75	0	0	0	0
26	156.22	20468.16	10234.08	22989.60	11494.80	18602.64	9793.29	20894.50	10447.25
27	146.98	115058.90	57529.44	129232.80	64616.40	166.92	87.87	187.48	93.74
28	160.05	121020.50	60510.24	135928.80	67964.40	4766.57	2509.34	5353.82	2676.91
29	157.29	32093.28	16046.64	36046.80	18023.40	0	0	0	0
30	150.84	47369.88	23684.94	53205.30	26602.65	3857.77	2030.91	4333.05	2166.52

The computed average values of PWI_G and PWI_T were 1,477 kg ha^{-1}yr^{-1} and 1,978 kg ha^{-1}yr^{-1}, respectively. These amounts were applied to obtain the yearly production of agricultural plastic waste (APW kg yr^{-1}) per municipality (Table 6).
The results demonstrated that Acate was the municipality with the highest amount of APW_G, 467,375 kg yr^{-1}, corresponding to the 37.5 % of the total APW_G deriving from A-shaped greenhouse cultivation system. The highest value of APW_T was found in Vittoria municipality where the computed yearly production is 417,978 kg yr^{-1}, almost the 29.5 % of the APW_T whole amount.

Table 6 - Agricultural Plastic Waste (APW) yearly amount

Municipality	Density [kg ha^{-1}]	$APWI_G$ [kg yr^{-1}]	$APWI_T$ [kg yr^{-1}]	Surface area [ha]
Acate	65.58	467,375	200,928	10,190
Chiaramonte Gulfi	0.01	100	100	12,659
Comiso	0.02	100	100	6,501
Giarratana	0.02	100	100	4,335
Ispica	21.32	3,928	236,943	11,297
Modica	4.35	22,564	103,708	29,048
Monterosso Almo	0.02	100	100	5,619
Pozzallo	11.55	3,072	14,279	1,502
Ragusa	10.90	274,838	206,944	44,181
Santa Croce Camerina	68.71	159,717	121,527	4,093
Scicli	9.84	20,437	114,902	13,757
Vittoria	39.28	294,287	417,978	18,135
Total	-	1,246,618	1,417,609	161,317

The entire amount of APW ($APWI_G$ + $APWI_T$) was computed for the whole province of Ragusa and reported on thematic GIS maps. Furthermore, two maps describing the quantity and the density, respectively, of plastic waste film yearly production (Figure 5 and 6) were elaborated.

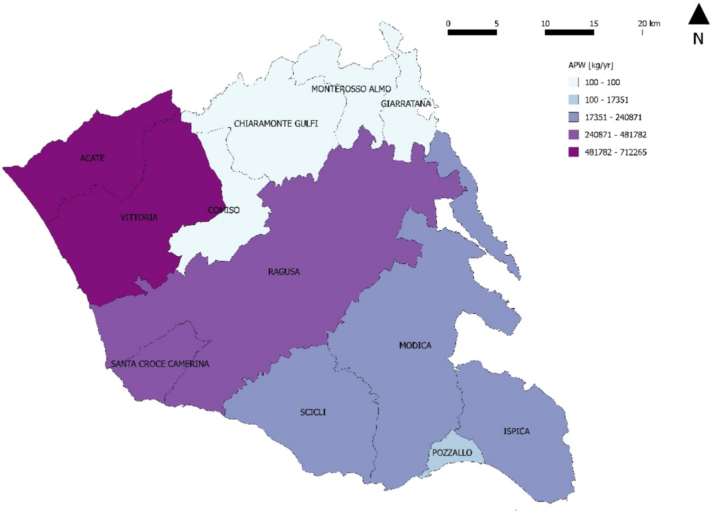

Figure 5-APW yearly amount in the municipalities of the province of Ragusa

As clearly highlighted in Figure 5, Acate and Vittoria resulted the municipalities with the greatest amount of APW, i.e., 668,303 (kg yr^{-1}) and 712,265 (kg yr^{-1}), respectively. Whereas Acate and Santa Croce Camerina municipalities reported the highest density, i.e., 65.58 (kg ha^{-1}) and 68.71 (kg ha^{-1}) (Figure 6).

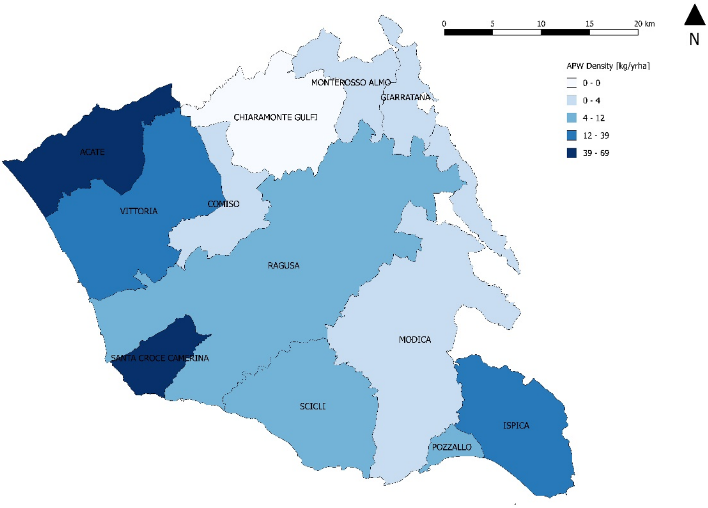

Figure 6 -APW density in the municipalities of the province of Ragusa

The analysis of the achieved results shows that, considering the mean value of PWI, the total amount of plastic waste deriving from covering films of protected cultivation is about 1,7 tons per hectare per year. The computed yearly amounts of APW, $APWI_G$, and $APWI_T$ per municipality are shown in Figure 7. By taking into account only the municipalities with the highest APW amount, i.e., Acate, Vittoria, Ragusa and Santa Croce di Camerina, $APWI_G$ values resulted higher than APW_T values, except for Vittoria municipality.

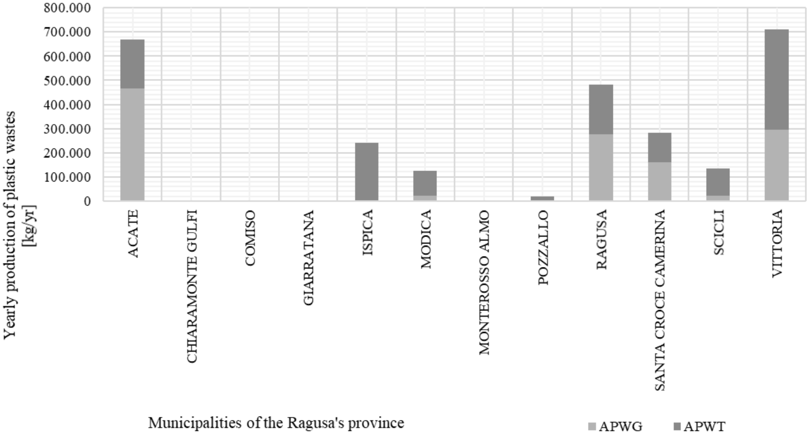

Figure 7 – APW total and APW$_G$

Figure 7- APW total, APWG deriving from A-shaped greenhouses and APWT deriving from tunnel-greenhouses computed for each municipality of the province of Ragusa.

2.7 Discussion

Through the GIS-model proposed in this study it was possible to compute the APW deriving from greenhouse cultivation system in the whole province of Ragusa, which was chosen for its relevance with regard to the development of protected cultivations. The obtained results concerning the amount and location of APW are essential for a better management of collection centers taking into account the existing infrastructures in order to optimize the collection process and reduce CO_2 emissions that is the major responsible for the global warming. During the research activities it was possible to observe that only one collection and recycling center was in the study area, in the municipality of Vittoria. Therefore, in view of obtaining new materials from APW and in order to reduce the transport cost for transferring APW to the recycling plants (De Montis, 2014; Osmani and Zhang, 2017), the optimization of the location of new collection centres is required. In this context, the GIS-model proposed in this study could be also used to plan the location of such collection centre by using the heat maps. This could also limit the APW mechanical recycling costs which often is higher than making plastics from virgin material because of the collection, transportation and cleaning costs (Demetres Briassoulis et al., 2013a).

Furthermore, the application of the GIS-based model to the study area made it possible to monitor at a municipality scale the state of application of the territorial policies aiming at the limitation of the environmental impact due to greenhouse cultivation system. The results of the research study showed that despite the indications of the Coastal Area Plan (CAP) contained in the Territorial Plan of Coordination of the Ragusa province (Country Council of Territory and Environment, 2004), a major part of protected crops is localized along coastline (Figure 4). In the study area considered for the GIS-based model application, the CAP had the aim of a 'reorganization of the coastal use' concerning agricultural activities, tourism, infrastructures, urbanization, etc., in order to reduce the anthropic load of this zone and allows the presence of ecological corridors in the coastal system. For a sustainable growth of the territory and assuring landscape quality, the requalification actions foreseen the displacement of greenhouses from coastal to rural areas. The CAP of the province of Ragusa directives were disregarded because protected crops are still concentrated in the coastal area. This result confirms the reluctance of farmers to move their agricultural activity far from the coast, probably because vegetable crops, especially tomatoes, suffer from the cold climate. So, this study confirms again what stated by Arcidiacono and Porto (2010) with regard the need of a policy action for the identification of new areas of agricultural value where greenhouse cultivation system could be moved as well as for providing incentives to farmers for the construction of new greenhouses far from the coasts. Public financial aids to farmers should be increased for both new land acquisition and installation of heating systems for greenhouses. Currently, in Sicily the PSR 2014/2020 supports the investments in agricultural sector ("Sottomisura 4.1") and aids farmers in order to modernize crops and production process. However, the contribute for the renovation of greenhouse system is too low and quite insufficient to delocalize protected cultivation far from the coast.

Moreover, the heated greenhouses are currently not widespread, and the passive greenhouses system still remain the most common. Therefore, new technological advancement should be supported and disseminated among farmers in order to win their reluctance to use new heating systems.

As demonstrated by applying the GIS-model, most protected crops are tunnel-greenhouses which are structures built with modern construction systems, replacing traditional greenhouses. This means a major consumption of plastic materials for the same quantity of covered surface, due to the greater slope of tunnel-greenhouse typologies, as reported in Table 4. In future the use of newer generation of biopolymers (plastics made from biomass sources materials) as covering films, currently used for mulching (Kasirajan and Ngouajio, 2012), could represent an alternative solution to cope with concerns related to agricultural plastic use. Meanwhile, the method proposed in this study could be useful to compute density and spread of these tunnel – greenhouses in order to make policymakers able to evaluate the financial aid for farmer to replace conventional covering films with more sustainable ones.

Finally, the research study reported in this paper is in line with the Waste Framework Directive (WFD) of European Union (Directive 2008/98/EC) that provides correct procedures for collection, disposal and recycling of post-consumption plastics in order to reduce the environmental effects of the use of plastics in agriculture. More specifically, Waste Management Plans (WMP), that is an obligation of EU Member States, must establishes the objectives to be achieved, to formulate strategies and to identify the implementation means to improve protection of environment and human health and to reduce impacts of the waste production and management. Since EU Member States can ask the regional or local authorities to put forward WMP on regional or local base, the GIS-based model proposed in this study could allow local authorities to manage APW deriving from greenhouse cultivation system.

2.8 Conclusions

In this study, a GIS- based model to locate and quantify the yearly amount of APW coming from greenhouses cultivation system was developed and applied in the province of Ragusa.

The index PWI to determine APW amount was chosen from literature and applied to obtain heat maps related to covering plastic films. Then, by taking into account different thickness, lifetime, and density of the covering films of the greenhouses within the considered samples, the index was computed and ranged between 976 kg $ha^{-1}yr^{-1}$ and, 2,484 kg $ha^{-1}yr^{-1}$.

The achieved results showed that the highest density of A-shaped greenhouses and tunnels-greenhouses is located nearby the coastline. Furthermore, the results obtained by the development the GIS-based model could be useful at a regional level since provide relevant information for the analysis of the environmental impact due to transportation of APW to collection centres, recycling industries or landfills located in the neighbouring of the study area. By using the GIS-model proposed in this research study local administrators could take advantage of a suitable tool for monitoring land consumption and putting forward adequate corrective actions to achieve the planned objectives and improve the sustainable disposal management of covering plastic films. In this context, the results of the study highlighted that the guidelines of the Territorial Plan of the Province of Ragusa were disregarded.

Moreover, from an economic point of view, if plastic materials are not recovered after their use, the European Commission Directives purpose to transform Europe into a more circular and resource efficient economy would be disregarded.

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3 Organized Framework of Main Possible Applications of Sheep Wool Fibres in Building Components

(Review, Published on Sustainability 2020, 12, 761; doi:10.3390/su12030761)

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Abstract

Greasy sheep wool is currently considered a special waste for its high bacterial load, with expensive disposal cost for sheep breeder. For this reason, wool is often burned or buried, with serious consequences for the environment. On the other hand, sheep wool is well-advised among the most performative insulation natural fibre due to its thermo-hygrometric and acoustic properties. In building sector, sheep wool responds to the requirements of green building components because is an eco-friendly material, a surplus, yearly renewable, and totally recyclable. If used instead of common insulation materials (e.g., fiberglass, rock wool, polyurethane foam, polystyrene), sheep wool offers significant benefits for sustainability such as a reduction of both productions cost for new insulating materials and environmental pollution. In literature, studies were conducted to explore properties of sheep wool for applications in building sector. The aim of this paper is to provide an organized framework of possible applications of wool fibres in building components. Performance tests carried out in previous studies were assessed and discussed in relation to the applications considered. This organized framework would highlight aspects not enough investigated to detect new potential use of sheep wool fibres in rural buildings and the reuse of traditional ones.

Keywords: *agricultural waste management; natural fibres; environmental sustainability; thermal-acoustic insulation.*

3.1 Introduction

Based on assessment of risks on environment, United Nation Environment Program stated that the construction industry is the sector with the highest environmental impact. Building sector is responsible for world global energy and water consumption, 40% and 25% respectively, and for 40% global resources utilization. To reduce ecological negative effects and consequent climate change, the construction sector should carry out sustainable solutions in order to decrease environmental pollution and consumption of resources such as materials, fuels and energy. In buildings up to 30% of heat loss can be avoid by external walls insulation, which the most sustainable actions to reduce energy consumption, economic losses, pollution, and CO_2 emission.

Energy efficiency of buildings depends on their thermal insulation improvement, on energy saving, and on CO_2 emission reductions. Therefore, a sustainable building process could be achieved by using natural insulation materials instead of those commonly used (e.g., polyurethane foam, polystyrene (EPS), fiberglass, mineral wool), in accordance with Green Building requirements (Wang et al. 2018).

Natural insulating materials (e.g., wood fibre and cellulose, sheep wool, hemp, cotton, and flax) are usually water vapor permeable and they can regulate internal air humidity through their indoor moisture absorption capacity.

Picuno et al. (Picuno 2016) underlined the importance of using locally available materials for rural building renovation. Sustainability of rural environment improves by using building materials locally available, recyclable, and characterized by lower energy consumption for their manufacturing. Moreover, if properly used, natural fibres provide thermal and acoustic insulation comparable to common insulation materials, but with a lower carbon footprint, that is the total amount of greenhouse gases produced expressed in equivalent tons of carbon dioxide (CO_2).

Among natural fibres, sheep wool is considered the best performing, suitable for both thermal and acoustic building insulation and, if used as reinforced fibres for adobe clay or cement mix, also for its mechanical characteristics (Korjenic et al. 2015).

Sheep wool is an agricultural waste produced by sheep breeding. Wool is a renewable, recyclable and environmentally friendly material. Due to its natural properties and composition (e.g., 60% animal protein fibres, 15% moisture, 10% fat, 10% sheep sweat and 5% impurities), sheep wool fibre is a material fitting different use in many fields and sectors, especially to improve building thermal efficiency.

At the same time, sheep wool is a special waste for its potential bacterial load, with high disposal costs for breeder because it should be landfilled for a correct disposal. So, often wool is illegally disposed (e.g., buried or burned), with a strong impact on soil and air.

In the context of a circular economy, the reuse of greasy wool could reduce both environmental pollution and energy consumption. By turning sheep wool in a new raw material, it is possible to produce innovative building materials and/or components fully complying with eco-friendly construction criteria and environmental certifications (e.g., BREEAM, LEED, DGNB, and Green Mark).

This paper aims to develop an organized framework of main possible applications of sheep wool fibres in building materials and/or components to be used for the construction of rural buildings or their renovation. Firstly, a literature review was carried out to assess strengthens and weakness of sheep wool application as insulation or reinforced materials in comparison with other common commercial ones. Since sheep wool is a natural material, its possible applications should be precisely defined by using proper measurements and simulations to verify functionality and durability. Studies conducted until now provide important results for a correct application of sheep wool in different building components such as external walls, internal partitions, and roofs. Based upon the literature review, thirty-five papers published between 1996 and 2019, were analysed in order to assess sheep wool fibre characteristics (i.e., physical and mechanical) and its use in building materials and/or components.

3.2 Literature review

3.2.1 Physical properties of sheep wool

In the last few years many studies have been conducted in order to evaluate the insulation properties for both natural fibres and recycled materials. Among research studies carried out on natural insulating fibres, those related to the application of sheep wool fibres are becoming a new research topic. Sheep wool fibre as insulating material has been far used in the construction field (Corscadden, Biggs, and Stiles 2014) for its thermal and acoustic properties.

A recent paper review (Dénes, Florea, and Manea 2019) was focused on the use of sheep wool fibre as building material and provides a collection of measurements and tests concerning its main physical properties. Thermal insulation was evaluated by comparing wool with polystyrene. Results showed that wool is very performing. In fact, wool thermal conductivity, that is the ability for heat to pass from one side of a material through to the other, it is between 0.038 - 0.054 [W/m K]. Sheep wool is also suitable to control indoor air relative humidity. Due to their chemical composition, wool fibres could absorb more than 35% of its weight in water without the sensation of humidity and, since absorption is followed by a desorption, wool contributes to maintain constant indoor air relative humidity.

Bucişcanu et al. (Rajabinejad, Bucişcanu, and Maier 2016) compared sheep wool, glass wool and polystyrene foam thermal conductivity, thermal resistance, thermal transmittance, water absorption, and sound absorption coefficient. Collected values are similar for different materials (Table 1), with a consistent reduction for sheep wool of embodied energy which is the energy used for production and transportation of a construction material.

Table 1 - Comparation of wool performances and common insulation materials

Insulation material	λ value	R value (100 mm)	Thickness for U-value	Density	Embodied energy	Sound absorption coefficient	Water absorption
	[W/m K]	[m^{2}K/W]		[kg/m^3]	[GJ/m^3]	[500-2000 Hz]	[% wt/wt]
Sheep wool	0.034 –0.067	2.5 – 2.6	180-200	18-23	0.11	0.77 (60 mm)	up to 35 %
Glass wool	0.032 – 0.04	2 –3	170	10-30	0.83	0.65 (100 mm)	0.2 %
Polystyrene foam	0.033 – 0.035	2.5 – 2.8	150	30-50	3.03	0.35 (50 mm)	0.03 – 0.1 %

Volf et al. (Volf, Diviš, and Havlík 2015) compared thermal, moisture and biological performances of some natural insulating materials such as sheep wool, hemp, flax, straw, and wood fibres. In detail, thermal capacity, thermal conductivity, volume density and sorption isotherm were evaluated. With regard sheep wool, they obtained the follows thermal characteristics: thermal conductivity 0.062 [W/m K], thermal diffusivity 1.03 [m^{2}s^{-1}], volume heat capacity 0.06 [J m^{-3}K^{-1}], specific heat capacity 2.02 [J kg^{-1} K^{-1}]. These values were near to those found for the other tested materials.

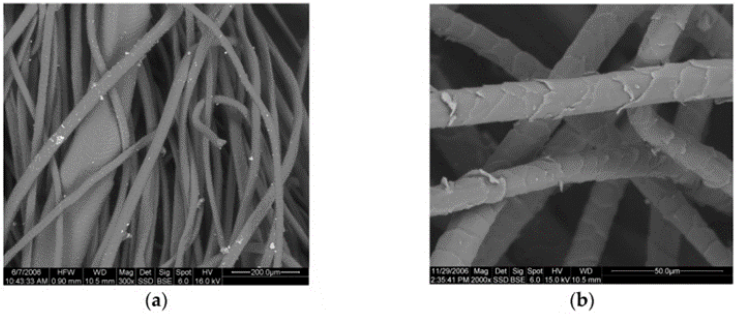
Other research works compared the thermal insulating capacity of sheep wool with rock wool eif, Zach, and Hroudová 2016; Zach et al. 2012). These studies, based on experimental measurements, showed that sheep wool is an excellent thermal insulation material very similar to mineral wool. Furthermore, by considering environmental aspects, sheep wool has many advantages as low transportation cost, because wool could be compressed with big reduction in volume, and highly energy efficient production. This is in accordance with results achieved in a study carried out in New Zealand and Northern Ireland that investigated the insulation performances of some sheep wool panels. Results showed that if wool density is more than 11 kg/ m^3 (Ye et al. 2006), thermal resistance is strictly correlated with panel thickness.

Jerman et al. (Jerman et al. 2019) in their study investigated thermal and hygric performances of five natural insulation materials, including sheep wool. The obtained experimental values for wool were low thermal conductivity, around 0.05 [W/m K], and high moisture diffusivity, achieved values ranged between 1.1×10^{-6} [$m^2\,s^{-1}$] and 1.2×10^{-5} [$m^2\,s^{-1}$]. These results show that wool is suitable to insulate building elements also without providing a vapor barrier system because the risk caused by water vapor condensation is contrasted by hygroscopicity of wool. Moreover, wool hygroscopicity contributes to improve air quality and regulate relative humidity of the indoor environment. In this study, it is also highlighted the importance of using natural materials for the renovation of traditional buildings because of the compatibility of sheep wool with the chemical composition of traditional construction materials.

Zach et al. (Zach et al. 2012b) within an interdisciplinary project conducted between Vienna University of Technology and the Brno University of Technology, performed detailed investigation with the aim to compare sheep wool and mineral wool behaviours. Thermal performance, sound absorption, hygrothermal properties and life cycle assessments have been evaluated. They stated that sheep wool is an excellent thermal and acoustic insulation material and that the high hygroscopicity of sheep wool fibres, which reaches up to 35%, prevents condensation, regulates humidity and creates a pleasant indoor atmosphere. Moreover, they found out that air flows in the pore structure of the insulation and bulk density of wool are inversely correlated, and that a better thermal insulation is achieved when bulk sheep wool density increases. Furthermore, they established that no additional acoustic benefit is achieved with material thickness greater than 170 mm. In conclusion, this study underlined the advantages coming from the use of wool instead of commonly used insulating materials such as, environmental benefits, ease of use, no negative health impact by handling the material, highly energy efficient production of the material, and higher fire resistance. Furthermore, they support the conclusions presented by Ballagh (Ballagh 1996) regarding the sound index reduction of more than six decibels by using sheep wool fibres for acoustic insulation, because sheep wool isolates better from vibrations respect to other analysed materials, such as rockwool or fibreglass.

Acoustic and thermal insulation of sheep wool have been also investigated by Korjenic (Korjenic et al. 2015). They found that sheep wool has good acoustical performances suitable as noise barrier, sound acoustic absorber inside room, or vibration insulator. The acoustic absorption coefficient of sheep wool panels tested in the study is between 0.84 [Hz] and 2.00 [Hz], higher than acoustic absorption coefficient of glass wool, polystyrene, mineralized wood fibres, and it is slightly lower than acoustic absorption coefficient of rock wool, polyester or kenaf fibres. Noise reduction under concrete slab is not very high (ΔLw = 18 dB) for sheep wool if compared with glass wool (ΔLw = 30dB) or expanded polystyrene (ΔLw = 31dB). However, it is similar to cellulose (ΔLw = 22 dB) or coco fibres (ΔLw = 23 dB) (Asdrubali 2006; Desarnaulds et al. 2005) noise reduction. Korjenic (Korjenic et al. 2015) also investigated a case of wall renovation by using an 8 cm thick layer of sheep wool insulating material. By using statistics and hygrothermal simulation programs it was carried out a building-physics assessment concerning moisture content and dynamic thermal transmittance. In detail, for the thermal transmittance (U-value) was observed a limited variation over the course of one year with minimal stress for building elements.

Most recent studies (del Rey et al. 2017, 2019) investigated the sound reduction index of sheep wool panels measured in a standardized laboratory (Figure 1).



(a) (b)

Figure 1 - electronic microscope details of sheep wool fibres (a) 200 µm rank; (b) 50 µm rank

Another study, part of the European project of Eco-Innovation Wool4build named “Improved Isolation Material for Eco-Building - Based on Natural Wool”, compared sheep wool fibres with other acoustic absorbent fibres as polyester fibres (PET), recycled foam, and mineral wool. Some typical acoustic characterization parameters such as airflow resistivity, normal-incidence sound absorption coefficient, and random incidence sound absorption coefficient were measured. Sheep wool samples with different composition have been tested, and the results showed that sheep wool can be considered a good acoustical insulation material.

Several studies also evaluated the sheep wool fire reaction. As reported by Dénes (Dénes et al. 2019) in case of fire, sheep wool does not contribute to the flame propagation since it carbonizes and does not burn. Wool is a self-extinguish material thanks to the high presence of nitrogen (Table 2). Wool fire reaction class is “E”. This agrees with (Zach et al. 2012b) and Saxena et al. (Saxena et al. 2011) works. By comparing wool with polystyrene, sheep wool presents most advantages because wool fibres burn slowly and in case of flame there is a slight sputtering. Furthermore, polystyrene is characterized by a very high flammability with toxic fumes production.

Table 2 - Chemical composition of raw sheep wool, in detail chemical composition of wool's keratin is reported.

Chemical Composition of Raw Sheep Wool			
Keratin	33%	Carbon	50%
		Hydrogen	12%
		Oxygen	10%
		Nitrogen	25%
		Sulphur	03%
Dirt	26%		
Suint	28%		
Fant	12%		
Mineral matter	1%		

Another potential use of sheep wool is as reinforced fibre for building components. In this context, some studies have been carried (Galan-Marin et al., 2016; Galán-Marín et al., 2010; Johnson et al., 2003; Mounir et al., 2015) with the aim of investigating the possible use of sheep wool inside different composite matrix, as unfired clay adobe or cement mortar. In their review Dénes et al. (Dénes et al., 2019) evaluated mechanical performances by comparing wool with polypropylene fibres used as concrete reinforced fibres. Compressive strength, flexural strength and tensile strength have been measured. Results showed that wool fibres are less performing than the polypropylene fibres. Researchers concluded that experimental measurements are strictly related to wool fibres length and to wool dosage within the used samples.

3.2.2 Mechanical properties of sheep wool

Fantilli et al. (Fantilli et al., 2017) examined the use of wool as mortar fibre-reinforcement. In detail, they tested cement small beams reinforced by untreated wool or by wool previously treated with atmospheric plasma, an ionized gas used for the modification of surfaces, in order to modify the nano-metric properties of the fibre surface. To compare the behavior of different vegetal fibres they tested also beams reinforced with hemp, largely investigated in the current literature. Three-point bending tests have been performed. The obtained results show that flexural strength and ductility increased when wool, untreated or not, is added to cementitious mortars. By adding 10 g of untreated wool, corresponding to 1% in volume, the flexural strength increases of 18% and the fracture toughness of 300%. In the same way, if an equivalent mass of cement mortar is substituted by 10 g of wool treated with atmospheric plasma (1% in volume) the flexural strength increases of 23% and the fracture toughness of 300%. Fantilli et al. (Fantilli et al., 2017) also stated that the sustainability of cement mortar improves by decreasing the cement quantity and substituting polymeric fibres with sheep wool. They indicated that additional tests must be performed with the aim of optimizing the composition of cement mortar by reducing the cement quantity and increasing fibre amount without consequence for workability and mechanical performances of the composite matrix. Statuto et al. (Statuto et al., 2018) performed compression tests on two different types of reinforced adobe clay, one mixed with 3% by weight of sheep wool and one with 3% by weight of wheat straw. The compressive strength of adobe bricks reinforced by sheep wool fibre was considerably higher than compressive strength measured for adobe clay reinforced with wheat straw.

Stirmer et al. (Stirmer N., Milovanovic B., Sokol J. M., 2014) in their study compared compressive strength, flexural performance, thermal insulation and density on different mortar mixtures prepared with Portland cement, crushed sand 0/4 mm, lime, expanded clay, metakaolin and chemical admixtures, sheep wool fibres (in amount of 3, 5 and 9 % per mortar mass, respectively). Obtained results showed that the addition of sheep wool fibres reduces the mortar density improving thermal insulation properties but cause a decrease of mechanical properties, in particular compressive strength decreasing.

Sheep wool fibres tend to degrade due to the reaction of wool with alkalis contained in cement composite.

They stated that sheep wool fibres are suitable for restoration of traditional buildings because sheep wool composition blends with original mortar.

Cardinale (Cardinale et al., 2017) evaluated the possible use of sheep wool fibre to increase thermal and mechanical performance on cement mortar panels. The aim was to optimize sheep wool percentage inside panel to obtain best performances. Among the different mixed combinations, it was found that best results could be reached with 2% of sheep wool. Mobili et al. (Mobili et al., 2018) proposed an interesting use of sheep wool as reinforcement fibre for a prefabricated clay sandwich panel for exterior enclosure. This panel results from a combination of different materials such as clay soil, water, calcium alginate and sheep wool fibres. Sheep wool to improve resistance to compression, bending and shearing and reduce shrinkage. Moreover, sheep wool also in this case contributes to the absorption of water vapor.

3.3 Building components in rural constructions

Currently, sheep's wool-based insulation products available in the building market are:

- soft mats made of 100% sheep wool, with thicknesses between 4 cm and 6 cm.
- rigid or semi-rigid panels made of sheep wool (70-80%) and polyester fibres (20-30%), with thicknesses between 5 and 12 cm.
- or rigid panels made of 100% sheep wool (Bosia et al., 2015);
- loose-fill fibres.

With regard clay or cement mortar – based adobes reinforced with sheep wool fibres they are not currently commercialized, and their possible applications are still at an experimental stage.

Sheep's wool-based insulation products are mainly used for the thermal and acoustic insulation of roofs, partitions wall, false ceiling roof. In the construction sector the sheep's wool fibres used to produce these building components are large and short and these characteristics make sheep wool unsuitable for textile sectors and destined to disposal.

Rural buildings, residential or not, are usually built without a specific temperature control system. Here below are describes some potential examples of critical issues that can be faced by using sheep's wool-based insulation products.

3.3.1 Roofs

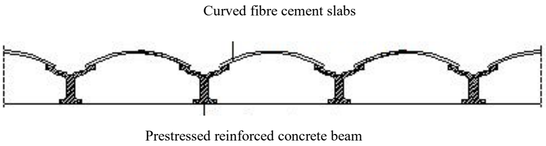
The employ of sheep wool as thermal insulating material of roof could represent a consistent advantage for some types of rural buildings where the control of microclimatic conditions is of relevant importance with regard to their main functional destination (i.e., buildings for intensive animal breeding, buildings for agroindustry). Sheep wool fibre is suitable for thermal insulation because its thermal parameters, reported in section 2.1.

In buildings for intensive animal breeding, a properly thermal insulation of building components more exposed to solar radiation (e.g., external walls and roof) allows animals to be defended from heat stress, especially during the summer season. When the outside temperature and relative humidity rise above levels well tolerated by animals, the mechanism by which they disperse excess heat goes into crisis. For example, in extreme climatic conditions, dairy cows are unable to dissipate heat through sweating and increase breathing rate to high latent heat loss. Firstly, to decrease metabolic heat production animals reduce food intake and physical activity and increase water consumption to disperse heat through their respiratory system. This new metabolic setting up causes a decrease in milk production, fat and protein concentration. These no healthy conditions for animals can occur for the whole summer season if a passive and / or active cooling systems are not efficient.

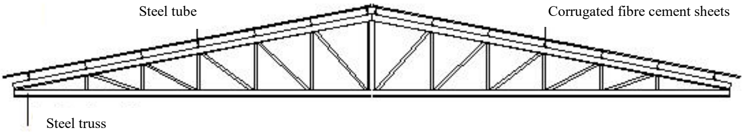
In buildings for intensive animal breeding, the load bearing structures of the roofs are frequently made with steel trusses or in prestressed reinforced concrete, while the roof covering is generally made of fibre cement slabs. Rarely, in such buildings, roof system is realized with wooden supporting structures and roofing tiles. This roof system is used in traditional rural buildings or in those recently built, or restored, that are included in protected areas subjected to landscape constraint.

By considering the most widespread roof typologies, there are three different types of roofs (Figure 2) built with:

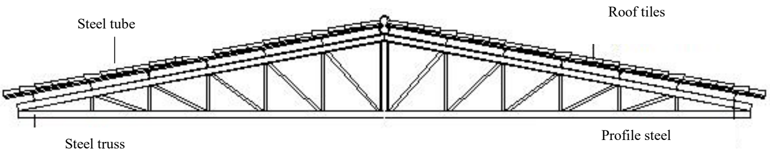
- a bearing structure in prestressed reinforced concrete covered with curved fibre cement slabs (Figure 2a);
- a steel supporting structure covered with corrugated fibre cement straight sheets (Figure 2b);
- a steel supporting structure covered with brick tiles (Figure 2c and Figure 3).



Roof realized with supporting structure in prestressed reinforced concrete and roof covering in curved corrugated fibre cement slabs.
a)



Roof made with steel supporting structure and covering in corrugated fibre cement straight sheets.
b)



Roof made with a steel supporting structure and a roof covering in brick tiles.
C)

Figure 1 – manly typologies of barn roof system

In some case, sheep wool insulation can be placed directly above the bearing structure. However, if the elements of the bearing structure are too far from each other, a secondary bearing structure could support the insulation layer (Figure 4). Suitable products that could be used for this scope are soft mats 100% sheep wool made.

Figure 2 - Barns roof system realized with wooden supporting structures and roofing tiles

Figure 3 - Example of sheep wool insulations on roof

3.3.2 External and internal walls

Sheep wool is appropriate for thermal insulation of external walls made of brick or stone masonry as well as concrete, either in warm and dry climate or in cold and humid one. In case of warm and dry climate, water evaporates from wool fibres and absorbs heat from the inside by keeping walls cool. In cold and humid climate, sheep wool absorbs water and prevents condensation in construction cavities by keeping the temperature above the dewpoint in damp conditions. The methodology to apply sheep's wool-based insulation products differs from cavity walls or solid walls. If an external wall has a cavity the insulation, semi-rigid panels or in loose-fill fibre, will be placed inside it without preparing the internal wall surfaces and the sheep wool thickness required will be the same of the cavity to be filled. In new construction to make sure that the insulation does not slip in the cavities a net support could be required. Sheep-wool panels insulation are simple to install as occurs for mineral wool panels. In solid walls sheep wool insulation will be placed on the indoor wall surface with a secondary structure able to support it.

Thermal performances of the indoor environment could be achieved also by using sheep wool to insulate internal walls. In detail, sheep wool has a relevant capacity to control condensation due to water vapor diffusion parameters and hygroscopic properties (e.g., moisture diffusivity 1.2×10^{-5} m^2 s^{-1}, hygroscopicity more than 35% of its own weight) (Jerman et al. 2019). Excess of air relative humidity is the main cause of mould with both detrimental effects on building' structure and risk for human health. The main advantage of using sheep wool as insulation material is its capacity to absorb the exceeding moisture without significant changes of its thermal performance as occurs instead for mineral fibre insulations that deteriorate. Through a chemical process, call chemisorption process, sheep wool is suitable to neutralize harmful and odorous substances such as Nitrogen Dioxide, Sulphur Dioxide, Toluene, and Formaldehydes. By using sheep wool insulation indoor air quality (IAQ) and human and/or animal wellness improve.

In some rural buildings such as flour mills, olive mills and wineries, the insulation of external walls is crucial to obtain optimal microclimatic conditions during the agroindustry process. In detail, within the grain supply chain one of the most important issues during the milling phase is to maintain constant the rheological characteristics of flours, semolina and wheat flours over time. In addition, the inadequate hydration of the flours can determine further problems related to the accomplishment of specific regulatory requirements; the occurrence of risks for consumers from mould formation; changes in grain characteristics that cause malfunctioning of the systems (Porto et al. 2015). Furthermore, an appropriate thermal insulation could contribute to improve the thermal condition of flour mills during heat treatments for insect pest control (Porto et al. 2017). Finally, since flour is an explosive material an important aspect to be considered is the fire reaction of mill building materials. Sheep wool is a natural fibre that doesn't contribute to the propagation of flame and has a fire reaction class 'E'. For the high presence of nitrogen within its composition wool is a self-extinguish material, burns slowly and, in case of flame, sputtering is low.

About olive mills, oil storage conditions (e.g., packaging material, oxygen, temperature, and light) modify both the fatty acid alkyl esters (FAEE) and other parameters (e.g., peroxide) that may cause the production of low-quality extra virgin olive oils (EVOO). During the long term oil storage, high temperature greater than 24°C causes degradation of oil quality meanwhile temperature lower than 8°C improves rancidity (Barreca and Praticò 2019). Thermal control of the oil storage area could be improved by using passive solutions and among them, insulation of internal partition walls by using sheep-wool made panels or soft mats could represent a proper solution.

Finally, a great number of wineries located in the Mediterranean area lacks specific temperature control systems to optimize wine storage and ageing process. Also in this case, sheep wool insulation could be used with the aim to obtain passive control of the indoor air temperature distributions and trends. Constant temperature and humidity levels inside production wine buildings could be achieved by an adequate internal insulation system, in addition to an external one. Wine aging practice is more influenced by air relative humidity and air temperature. If wine is stored in conditions that are too dry, the cork will shrink and cause leakage, if the air is too moist, mould and contamination may occur. To avoid these problems and reach the optimum wine development condition, air relative humidity levels in wine aging cellars should be kept constant, about more than 70% (Tinti et al. 2015). Due to its hygroscopicity sheep wool is the most suitable natural insulation material to create these microclimatic indoor conditions. Furthermore, wine production process is sensitives to temperature changes. The most ideal microclimate condition for wine storage and aging is a temperature range between 9° C and 20° C, with maximum air temperature fluctuation of 6° C. If wine is exposed to too high temperature, i.e., more than 25 °C, for long periods of time, it may be spoiled and could develop bad off-flavours. In case of too cold temperatures, wine can freeze and expand by causing the pushing of cork or the bottle cracking. A wrong range of air temperature can also produce adverse chemical reactions that may cause wine faults. Moreover, wine should not be kept in a refrigerator since the cooling process often includes dehumidification which could dry too quickly corks and allow oxygen to enter the bottle. For all these above issues, a passive control system of air temperature and humidity by sheep-wool made insulation materials is a solution for the whole wine production process.

3.3.3 Concrete slab floor

In agro-industrial buildings, machine vibrations cause unpleasant conditions for both workers and processed products. For instance, during red wine production process to limit changes in physicochemical properties of the stored wines, indoor vibrations should be minimized.

Sheep wool isolates better from vibrations respect to other materials, such as rockwool or fibreglass. In detail, sheep-wool made materials, such as soft mats, could be employed for the acoustical insulation of concrete slab floor. This kind of building solution should be carried out in agro-industrial buildings such as olive oil mills, pasta factories, flour mills, and, especially, when production process is not only limited to short periods but is extended whole year. Sheep-wool made insulation materials, i.e., loose fibres or soft mats, should be applied directly on concrete slab by using a wooden secondary bearing structure. This type of building intervention when is carried out on existing buildings determines an increase of about ten centimetres of the floor level because of the thicknesses of both sheep wool soft mats and wooden secondary bearing structure.

3.4 Critical Analyses on the reuse of sheep wool fibres and future research development

This critical analysis on the reuse of sheep wool in building components regards its long-term performance and availability.

Long term performance of natural materials should be considered because of their biological composition. Regarding sheep wool, the most critical disadvantage is its vulnerability to fungal and insect attacks. Mould growth on the surface of sheep wool-made materials is a potential allergenic powered by dust particles. The most common kind of wool moulds that cause allergy and asthma are: *Alternaria* alternate, *Stachybotrys* species, *Acremonium* species, *Penicillium* (biverticillata), *Fusarium* species. However, despite high hygroscopicity of sheep wool, laboratory tests showed that mould growth durability and susceptibility of common mould strains is low (Volf et al., 2015).

Another critical aspect to be considered for sheep wool reuse is its potential pathogenic bacteria load that is a critical point for breeder because it must be disposed as special waste with heavy financial and management costs. In fact, the European Hygienic-Sanitary Regulation concerning animal by-product management, i.e., storage and disposal, considers sheep wool an agricultural by-product only if it is submitted to some specific treatments, even a simple washing, in order to lower its potential pathogenic bacterial load (Europea, 2002; Regolamento CE, 2009).So, before any use greasy sheep wool must be washed, and in some cases carded. Additionally, to prevent attacks by fungal and insects, especially moths, a treatment with biocide (e.g., acid boric) should be required. Sometimes, during the manufacturing process of sheep wool panels, highly toxic anti-moth products are used, such as permethrin, that reduce the sustainable reuse of sheep wool.

Lastly, sheep-wool made insulation materials available on market are produced by few manufacturers. In Italy, these products are manly made of wool imported from foreign countries as Austria or New Zealand (Stirmer N., Milovanovic B., Sokol J. M., 2014). For this reason, sheep-wool made insulation products are generally more expensive than conventional insulating. Since the sustainability of sheep wool-made product depends on the availability and geographical location of greasy sheep wool specific analyses should be carried out on a territorial scale to investigate its possible re-use on a short supply chain.

Therefore, as part of a Ph.D. carried out within the International Doctorate in Agricultural, Food and Environmental Science of the University of Catania (Italy), with the aim of study possible alternative use of agricultural waste, i.e., sheep wool, a methodology was put forward to locate and quantify the availability of sheep's wool in an area of southern Italy strongly characterized by the breeding of dairy sheep, whose fleece is not suitable for textile industry. In Italy the number of sheep is around 7.4 million with the largest number in Sardinia (3,301,837), Sicily (906,069), Lazio (743,823), and Tuscany (422,734) (Table 3).

Table 3 - Consistency of the Italian sheep population divided by region in the year 2017 (Source processing IZS)

Italian regions	Number of sheep
Valle d'Aosta	2,215
Liguria	13,588
Friuli Venezia Giulia	23,221
Trentino Alto Adige	92,732
Emilia Romagna	59,907
Molise	71,279
Veneto	75,988
Umbria	116,898
Lombardia	129,869
Piemonte	135,172
Marche	150,538
Abruzzo	202,959
Campania	213,870
Basilicata	248,456
Puglia	264,675
Calabria	269,456
Toscana	422,734
Lazio	743,823
Sicilia	906,069
Sardegna	3,301,837

Sicily is the second region in Italy for number of sheep, after Sardinia. By analysing data supplied by National Zootechnical Registry (January 2019) of the Italian Ministry of Health, the number of sheep in Sicily was geo-referenced and quantified on a province base to obtain the geographical areas where the production of this by-product is higher, and the problem of its disposal is potentially relevant (Figure 5).

Future development of this research activity will be focused on the production of earthen adobes and panels made with raw earth and crushed sands, reinforced by sheep wool fibres. Raw earth buildings, warm in the winter and cool in the summer, are widespread in the world, also in regions very different for climate and land configuration. These constructions are important for a sustainable development of the building sector with a low impact for the ecosystem, though high level of seismicity could limit their use as occurs in Italy, where technical regulations allow for raw earth buildings only if associated with wooden bearing structures (Giuffrida et al., 2019).

During the research study, the mechanical and thermo-acoustic performances of sheep wool-made building components will be compared with that provided by similar ones obtained by using other natural fibres (e.g., hemp and straw). Self-supporting adobe clay, reinforced with sheep wool, will be manufactured, and tested by changing wool content and fibres disposition.

Based on the achieved results, the possible use of these components in rural building such as agro-industrial buildings and animal housing, will be investigated (Aymerich et al., 2012). By considering these kinds of rural buildings, they are manly made of conventional materials (e.g., concrete, steel, and plastic), with high environmental negative impact. The use of renewable raw materials locally available, such as raw earth and natural animal or vegetal fibres, could improve the sustainability of rural buildings (Georg and Ashour, 2015).

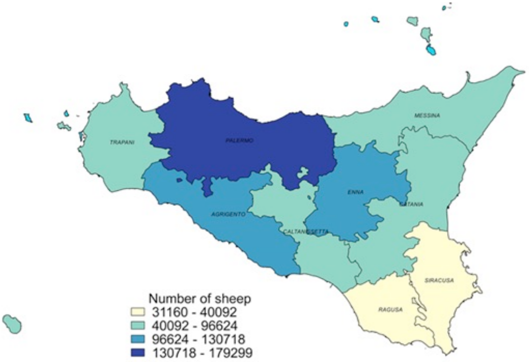


Figure 5 – Number of sheep in Sicily localized and quantified on a province scale

3.5 Conclusions

A holistic assessment of sustainability and energy efficiency in buildings must consider primary energy demand, CO_2 reductions, and ecological properties of the building materials, traditional or not. The use of sheep wool fibre is challenging to improve thermal efficiency of rural building. In this research work is proposed an organized framework with the aim of providing information suitable to optimize passive conditioning systems that could be also extended to other rural buildings.

The valorization of the locally available materials, such as agricultural co-products or by-products, and their use on rural buildings plays a crucial role especially in the agricultural areas. This is in accordance with the past tradition when the only possibility for farmers was to use local materials. Sheep wool is a potential sustainable raw material, continuously renewable, healthy for both production process and application, locally available, with a low manufacture energy consumption, and environmental impact.

Despite this, the utilization of natural insulation materials, such as sheep wool, is not yet widespread, and in some cases, is limited at laboratory stage.

Moreover, aspects concerning whole manufacturing process to convert raw wool into building materials, such as the correct scale required for a sustainable production of sheep wool insulation products, should be further investigated.

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4 Raw earth-based building materials: An investigation on mechanical properties of Floridia soil-based adobes

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Abstract

Raw earth, with wood and stone, has a place among the oldest building materials used in the world. Nowadays, on a circular economic context, researchers' interest in raw earth-based building materials has been growing because they are highly available and environmentally friendly. The use of this traditional material has positive environmental consequences, especially in traditional rural building reuse and in rural landscape preservation. In fact, raw earth is locally available and totally recyclable and, thanks to its perfect integration into the landscape, it improves site visual perception. Often, in order to increase mechanical performances and durability of earth materials additives and/or chemical stabilizer agents (i.e., Portland cement) are used to produce raw earth-based building components. This production process reduces the environmental sustainability of the base material and causes a relevant increase on the embodied energy. This research work aimed at investigating how to improve the mix-design of earth-based building materials in order to increase their mechanical properties without addition of chemical agents.

A physical stabilization was performed on an original texture soil, through the addition of different particle sizes. Mechanical tests have been carried out on five different soil mixes by changing soil composition, aggregates, and water. Specimens realized with the mix-design 5 showed best results of flexural and compressive strength values with 1.65 MPa and 6.74 MPa, respectively. Mix 3 obtained the lower linear shrinkage rate (6.04%).

Since raw earth-based materials are highly sensitive to soil composition and aggregates, the attempt of this study is to obtain a repeatable process to produce semi-industrial adobes by the optimization and control of different natural materials (i.e., soils, aggregates, and water).

Keywords: *raw earth building components, physical stabilization, mechanical tests, circular economy, sustainability*

4.1 Introduction

The rediscovery of raw earthen constructions and raw earth-based building-components is becoming an important topic in the construction sector because raw earth is highly available and environmentally friendly. Worldwide among traditional building materials used through centuries, raw earth has a prominent place. As stated by Guillaud *et al.* (2017) , one-third of the world's population lives in earthen dwellings and raw earth buildings are widespread in many countries from Latin America to Africa, from Central Europe to Middle East, especially in rural areas (Guillaud 2008). Raw earth could be extracted and worked directly in the building site with significant reduction of environmental costs for supplying due to the related transport pollution (Gallipoli et al. 2017). This is an important aspect to be considered in order to improve the environmental sustainability of rural building renovation or construction.

The use of raw earth has positive environmental consequences, especially in traditional rural building reuse and in rural landscape preservation. In fact, raw earth is locally available and totally recyclable and, thanks to its perfect integration into the landscape, it improves site visual perception (Picuno 2016).

Furthermore, raw earthen constructions and raw earth-based building-components satisfy indoor thermal and acoustic comfort with also the capacity to absorb toxic volatile compounds (Fagone et al. 2019). In fact, due to their breathability and high thermal mass, raw earth building materials could stabilize hydrothermal indoor conditions and control temperature variation, especially during hot season. Despite the aforementioned benefits connected to the use of raw earth materials, the development of earthen constructions is currently limited because of the difficulties in controlling the mix design and the high vulnerability due to the washing action of rainfall. In addition, quality specifications for the technological process are lacking and often structures are wrongly dimensioned. Barbari et al. (2014a) proposed a simple structural calculation method in order to satisfy the minimum structural safety requirements for earthen buildings. This method is suitable especially for rural areas in developing countries

"for both the construction of buildings and the training of local technicians" (Barbari et al. 2014a).
Moreover, a weakness point of the production process of raw earth-based building materials is the long time required to harden and the high manual labor cost. Some of these problems could be solved by adding aggregates to the mix design (e.g., synthetic binders, cement, and admixtures) that improve the mechanical behavior of the earth-based building components and accelerate the hardening process (Perrot et al. 2018). Some study reported how the cement production process developed in the concrete industry can be applied to earthen construction in order to improve their performance (Giuffrida, Caponetto, and Cuomo 2019). Further innovative processing methods like self-compacting clays, hyper compaction and extrusion, have also been used to improve workability of raw earth building materials and reducing the curing time (Ouellet-Plamondon and Habert 2016).

Numerous studies proposed the addition of reinforcements fibers to raw earth adobes mix in order to improve their mechanical behaviors. Araya et al. (2018) assessed the use of animal fibers, (i.e., pig hair), in adobe mixes. In this study, the experimental evaluation included flexural toughness, flexural and compressive strength, ultrasonic pulse velocity, drying shrinkage distributed cracking, and impact strength tests. Mechanical behavior of raw earth adobe mixes without fibers was compared to adobe specimens reinforced with pig hair. The results of the mechanical tests showed that addition of fibers reduced flexural and compressive strengths, in particular compressive strength value found was 1.20 MPa for adobes with fibers and 2.02 MPa for adobes without fibers. On the other hand, addition of pig hair in adobe mixes increased flexural toughness and reduced drying shrinkage (Araya-Letelier et al. 2018). Statuto et al. (2018), compared the mechanical properties of adobe made with natural fibers (i.e., sheep wool and wheat straw) with those obtained without adding fibers (Statuto et al., 2018). The results showed that the compression strength values of adobes made without fiber addition was higher than that incorporating vegetal fibers, respectively 2.05 N/mm^2 and 1.86

N/mm^2, while the addition of animal fibers to the mix improved the compression strength value significantly, reaching about 4.32 N/mm^2.

With regard to the mechanical properties of raw earth-based building components, their performances depend mainly on the correct selection of the mix design in the production process. In the study proposed in this paper, the mechanical properties of five different soil mixes have been evaluated and compared with the aim to obtain best performances without adding chemical stabilizers. Therefore, the novelty of this study relies in the attempt to find an optimal mix recipe to build adobes made of a type of earthen material produced from a clay present in Sicily, formerly traditionally employed for the production of bricks, and a pyroclastic sand typical of the Etna volcano area (Sicily), commonly used for mortars and concretes production (Belfiore et al. 2020).

4.2 Materials and method

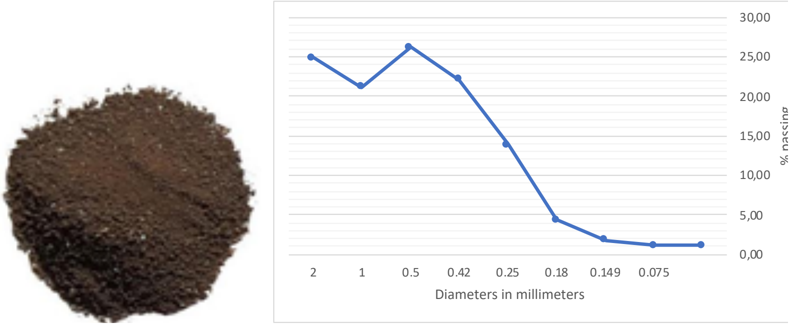
4.2.1 Soil

In a recent study (Giuffrida et al. 2019), five Sicilian soils were analyzed in order to select the most suitable for raw earth materials: chemical composition, plasticity and particle size had been evaluated. After these qualitative experimental analyses, a soil extracted close to Syracuse named "*Terra di Floridia*" (Figure 1a) was selected because of its higher amount of clay, easy extraction, and lower transport cost. Floridia soil (FS) was classified as a kaolinite soil, with 47,30% Liquid Limit (LL), 30,68% Plastic Limit (PL) and 16,62% Plasticity Index (PI= LL - PL).

Kaolinite soils thanks to their limited specific surface area (about 10 m^2/g) if wet or dry have a reduced swelling and shrinkage (Gallipoli et al. 2017).

The grading of FS is shown in Figure 1b. Particle size distribution was determined through a sieve analysis carried out in accordance with the ASTM D7928 – 17 requirements, by using material dried in an oven at 100 °C.

FS was modified (FS^M) according to an optimization procedure with the aim to improve its mechanical behavior through a physical stabilization process (Achenza and Sanna 2009). The particle size distribution of FS has been changed through the addition of clay, in the proportion of 58% FS soil and 42% clay, in weight. In literature good results have been achieved with a similar soil composition (Galán-Marín, Rivera-Gómez, and Bradley 2013).



(a) Floridia's soil **(b) Grading of Floridia's soil**

Figure 4 – Floridia's soil used in the experiments

Clay improves plasticity, mechanical characteristics, and cohesion, and can reduces water absorption enhancing erosion resistance to wind and waterproofing toward capillarity water. To prevent shrinkage and cracking problems and to improve mechanical resistance, FS^M and clay have been mixed with pyroclastic sand sieved to 2 millimeters. Pyroclastic sand used is called 'azolo' and it is typical of the Etna volcano area. 'Azolo' is formed on the surface of lava by the crushing of glassy materials generated by the quick cooling of magma.

4.2.2 Sample Manufacturing Process

Once the material mix was ready, specimens were manually made and compacted. The process of specimen preparation started with the addition of sand, in different percentages, to FS^M and after, when the blend was completely homogeneous, water was manually added in four steps by mixing between each addition.

In accordance with the European standards (EN 1015-11:2019) for the mechanical testing of mortar, 6 prismatic samples 160 *mm* × 40 *mm* × 40 *mm* were prepared for each different mix. Standard steel molds for prismatic specimens, previously moisturized to prevent adherence, were used. The specimens were cast in consecutive layers and manually compacted. Three days after the casting, specimens were demolded and kept in an open space in dry conditions (temperature ranged between 13.1 °C -15.5 °C and air humidity between 76.7% - 80%) for 28 days for curing before testing. Similar curing procedure is in accordance with New Zealand Code (NZA 4298 1998) and it was used in previous researches, also with non-cement stabilized earth samples (Türkmen et al. 2017).

The five soil mixes reported in Table 3 were tested to assess the influence of water and sand percentages on the mechanical properties. For each mix, six repetitions were prepared. By following the same methodology indicated for a physical stabilization without addition of any chemical agent (Hall and Djerbib 2004), soil mixes numbered 1, 2, 3, 4 and 5 were made by increasing sand percentage from 25% up to 35% and decreasing the FS^M percentage, from 60% to 45%.

To get a consistency easy to be worked and a low total shrinkage, all samples were produced by using 20% of water and 80% of soil (FS^M added with sand) except for the specimens built with mix 4 which were made by using 25% of water and 75% of soil. This increment of water was required in order to improve the workability of the mix.

Table 3 - Soil mixes

Soil mix ID	FS^M [%]	Sand [%]	Water [%]
1	60.00	20.00	20
2	55.00	25.00	20
3	50.00	30.00	20
4	42.00	33.00	25
5	45.00	35.00	20

4.3 Mechanical resistance tests

Since an earth-based building material is heterogeneous and anisotropic, the methodology used to carry out the mechanical tests (e.g., flexural and compressive strength) was the same used for natural and artificial stone. Therefore, 30 specimens, i.e., six repetition for each mix, were tested for flexural and compressive tests by following the standard EN 1015-11:2019.

The trials started by carrying out the flexural tests for each specimen. Then once each specimen failed, the two parts obtained were tested under compression. In correspondence to the maximum load reached during the tests, breaking loads were determined.

Flexural strength of each beam specimen was assessed by applying a single point load at the mid-span of the prismatic specimen. The test setup was mounted on the Universal Testing Machine (UTM) by positioning the sample inside two lower rollers supports (Figure 5 a) with 100 mm of wheelbase. UTM was connected with a Load Cell Hottinger Baldwin, and load values were recorded for each specimen from the start of the test until the sample breaking, applying a load of 10 N/s. Data acquisition was implemented by Catman Software for Tests with Huge Channel Counts.

Flexural strength value (σ_f) of each specimen was determined using Eq. (1), where F is the maximum applied load, L is the span between supports (100 *mm*), b is the width of the specimen at the mid-section and d is the average depth of the specimen at the fracture section.

$$\sigma_f = \frac{3\,F\,L}{2\,b\,d^2} \qquad (1)$$

Compressive strength value (σ_c) was determined by Equation 2, by carrying out the compressive tests of the two remaining prismatic parts obtained after the flexural fracture of each beam specimens (Figure 5 b). The samples were renamed keeping the flexural ID by adding number 1 and 2.

$$\sigma_c = \frac{F}{S} \qquad (2)$$

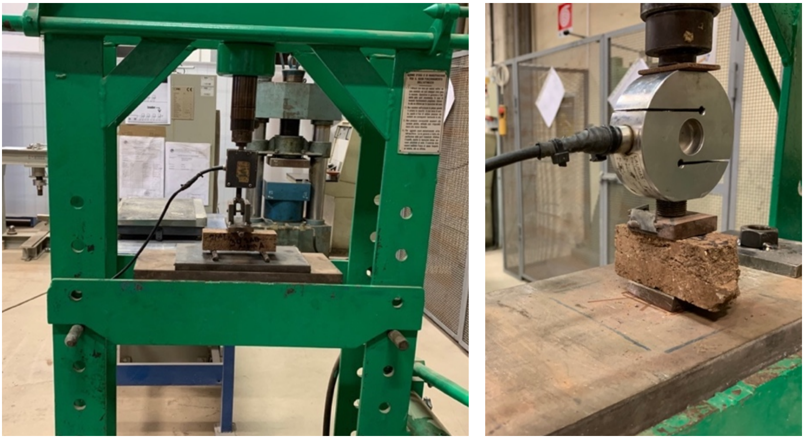
In the Equation 2, F is the maximum applied load and S is the area of the loaded section.

During the drying process in the brick occurs a physical phenomenon called shrinkage due to the evaporation of moisture content. Shrinkage causes the cracking of the material due to some residual adherence of the soil to the mould and a continuous and fast drying.

For earth materials, linear shrinkage is commonly evaluated in accordance to testing method ASTM C326-09, the linear drying shrinkage (S_d) was calculated by using Equation 3,

$$Sd = \frac{Lo-L}{Lo} \times 100 \qquad (3)$$

where L is drying length of specimen after 28 days, measured by using a calibre, and L_0 is the internal length of mould (160 *mm*).



a. Flexural strength test **b. Compressive strength test**

Figure 5 - Universal Testing Machine connected with a Load Cell Hottinger Baldwin used to carry out the mechanical resistance tests

4.4 Results and discussion

Flexural strength could be considered as an indicator of the capability of energy absorption. The maximum value obtained was 1.65 MPa for soil mix 5 and the lower equal to 0.89 MPa for specimens realized by soil mix 4. This minimum value is probably due to a greater water percentage in the mix, 25 % instead of 20%. Specimens sudden drop in load because of the formation of unstable macroscopic crack after the maximum load is reached (Figure 6).

The average of the flexural strength values computed for each mix design are compared in Table 2.

After the flexural failure, compressive strength tests were carried out for each part of the specimens and Table 3 shows the average values obtained for the 5 soil mixes. The highest value was 6.74 MPa for the soil mix 5, the smallest value was 3.05 MPa for the soil mix 4. As already stated in the previously paragraph this low value is probably due to the greater amount of water used in the mix.

Shrinkage rate for specimens related to the different mixes were obtained by equation 3. As expected, specimens made with the soil mix 4 showed the highest shrinkage rate, corresponding to about 8.23%. Specimens made with the soil mix 5 exhibited the lower shrinkage rate 6.04% (Table 4).

Figure 6 - Failure mode of specimens

The results of this research study showed that compression strength values ranged between 3.05 MPa and 6.74 MPa. These values were above the minimum required by the most important raw earth construction international standards, such as 1.3 MPa required from New Mexico Earthen Building Code, and 2.0 MPa imposed by New Zealand Regulation. Soil mix 5, made of 45% ES, 35% sand, and 20% water, exhibited the best upshots. In fact, the compression strength vale was 6.74 MPa and the flexural strength was 1.65 MPa. These values are significantly higher than other results found in previously studies. Araya *et al.* (2018), Statuto *et al.* (2018), compared the mechanical behaviors of raw-earth adobes made with natural fibers to those with those obtained without adding fibers without addition. Raw earth adobes without fibers exhibited compression strength ranging between 2.02 MPa and 2.05 MPa and flexural strength around 0.49 MPa (Araya-Letelier et al., 2018; Statuto et al., 2018). The higher values obtained in the trials carried out in this study are mainly due to the soil mix that incorporates a siliceous inert like "azolo" that, commonly used in the concrete industry, gives high resistance to compression. With regard to flexural strength, it ranged between 0.89 MPa and 1.65 MPa. Also these values are greater than minimum required in some international code, such as the New Zealand Regulation that indicates at least value of 0.25 MPa (New Mexico 2009; NZA 4298 1998). All flexural strengths obtained in this study ranging between 0.89 MPa and 1.65 MPa are above this minimum value. Moreover, the obtained flexural strength values are below 25% of the related compressive strength values. This is in line with other results obtained in similar study where flexural strength lied below 30 % of compressive strength with a compressive strength multiplier of 3.5 times flexural strength (Barbari et al. 2014b). By analysing the obtained results, it is evident that maximum loads, compressive and flexural strengths increased for specimens with a higher quantity of "azolo" sand. Moreover, by considering standard deviation of flexural strength values, specimens with higher percentage of sand have a lower standard deviation.

Table 2 - Average of the flexural strength values obtained for the five soil mixes

Soil mix no.	Average Maximum Load [N]	SD	Average Flexural Strength [MPa]	SD
1	411.06	7.97	1.27	0.28
2	529.62	8.87	1.57	0.26
3	529.95	5.34	1.52	0.14
4	345.00	6.90	0.89	0.19
5	546.91	1.76	1.65	0.04

Furthermore, as shown in Table 3 specimens of soil mix 5 have a low density but it exhibits the best characteristic strength. This means that, as already observed in previously study, no correlation was found between dry density and compressive strength of the samples (Ciancio, Jaquin, and Walker 2013). To determine the relationships between dry density and compressive strength the correlation coefficient has been evaluated. The result was a low correlation coefficient, R^2 0.14.

Table 3 - Averages of the compressive strength values obtained for the five soil mixes

Soil mix no.	Average maximum load [kN]	SD	Average dry density [kg/m³]	Average compressive strength [MPa]	SD
1	7.72	0.52	1960,00	4.82	0.32
2	10.14	0.75	1980,00	6.34	0.47
3	10.22	0.98	2150,00	6.39	0.61
4	5.09	0.68	1960,00	3.05	0.43
5	10.95	0.81	1960,00	6.74	0.35

With regard shrinkage rate, soil mix design 3 reached the lower rate equal to 6.04%. However, by considering the acceptable values of raw earth shrinkage, the shrinkage rate is too elevate for all mix design (Woyciechowski, Narloch, and Cichocki 2017). As already demonstrated in a comparative analyses, shrinkage rate could be reduced by the addition of both natural or artificial fibers in the mix design (Vega et al. 2011).

Table 4 - Averages of the shrinkage rate values obtained for the five soil mixes

Soil mix no.	Average shrinkage rate %	SD
1	6.98	0.18
2	7.29	0.18
3	6.04	0.36
4	8.23	0.65
5	6.25	0.05

4.5 Conclusions

Mechanical tests have been carried out on five different soil mixes by changing soil composition, aggregates, and water. The original texture of soil “terra di Floridia” (FS) was modified through the addition of different particle sizes, by performing only a physical stabilization on the soil. Firstly, to FS was added clay, by obtaining a soil composed of 58% FS soil and of 42% clay (FSM). After, in order to improve its mechanical behaviour, to FSM was added a pyroclastic sand, called “azolo”, highly available in Etnean area. By changing sand percentage (from 20% to 35%) and water content (20% or 25%) five different mix design were tested. Flexural and compressive strength, and linear shrinkage have been evaluated. Good results have been achieved for all the mechanical resistance tests, except for linear shrinkage which exhibits a too high rate, from 6.04 % to 8.23 %.

To reduce shrinkage rate and improve ductility in the failure mode, a future research work will study the addition of natural fibres, such as sheep wool, to the mix-design 5 that showed best results of flexural and compressive strength. The reuse of this special agricultural waste as reinforcement fiber for raw earth building materials, could be relevant in order to give a contribute towards environmental sustainability of the building sector (Parlato and Porto 2020). In fact, the improvement of the mechanical resistances of raw earth-based materials by using natural fibres coming from a special agricultural waste such as sheep wool, could reduce both resource consumption and environmental pollution.

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5 Natural Fibers Reinforcement for Earthen Building Components: Mechanical Performances of a low-Quality Sheep Wool ("Valle del Belice" sheep)

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Abstract

The paper proposes the use of Sheep wool fibers (SWF) deriving from the fleece of domestic sheep ("*Valle del Belice*" from Sicily) as reinforcement for rammed earth building components. Addition of natural fibers to the mix design of earth-based building materials allows to improve their tensile strength, ductility, impact resistance, toughness, and to reduce drying shrinkage. To this aim, an experimental campaign on more than 180 fibers has been carried out, determining the main mechanical properties of interest for their use as reinforcement. Since wool is highly hydrophilic, three different conditioning programs (wet, dry and an intermediate condition) were compared, in order to get useful information about the preservation of the mechanical properties in wet environments like those present in lime mixes. The dependency of the properties from the fibers' diameter was investigated, and the results were statistically analyzed using a modified Weibull distribution as function of the fiber diameters, finding a strong correlation with the mechanical properties.

The use of natural fibers as reinforcement could enhance the environmental sustainability of the building components, especially when natural fibers are obtained from agricultural wastes deriving from sheep of low-quality wool not used in the textile industry and that must be disposed of in landfills.

Keywords: *natural fibers, sheep wool, tensile strength, mechanical testing, statistically Weibull distribution, raw earth materials.*

5.1 Introduction

Earth constructions and earth-based building-components are becoming popular in the building sector due to their low environmental impact and sustainability. Among traditional building materials used throughout the centuries all over the world, raw earth has a prominent place. As stated from Guillaud et al. (Guillaud 2008) one third of the world's population lives in earthen dwellings; raw earth buildings are widespread from Latin America to Africa, from Central Europe to Middle East. Raw earth could be extracted and transformed directly in the building site, with significant reduction of environmental costs of transportation and related pollution. This is of relevant importance because improves the sustainability of the building sector, for building renovation or new constructions. Raw earth materials exhibit low tensile strength, so they have a reduced ability to respond to horizontal actions, like those occurring in seismic areas. For this reason, reinforcement fibers could be added to raw earth mix design to improve the tensile strength, ductility, impact resistance, toughness (Imanzadeh et al. 2020), and to control drying shrinkage and cracking resistance. Synthetic or natural fibers are suitable for this use.

In literature, several studies concerning the use of natural fibers as substitute of synthetic ones in soil matrix composites have been published (Hejazi et al. 2012; Kandemir et al. 2020; Sharma, Marwaha, and Vinayak 2016). Natural fibers are replacing synthetic fibers because of their economic and environmental sustainability, and for some peculiarities of their mechanical performances. In fact, natural fibers, in addition to environmental advantages like good availability, low cost, renewability, biodegradability, present a very low density, (i.e., natural fiber density is ranged between 1.2–1.6 [g/cm^3] lower than glass fiber density 2.4 [g/cm^3]) and generally guarantee good mechanical properties (Mulenga, Ude, and Vivekanandhan 2021).

Natural fibers can be vegetable with a lignocellulose structure (e.g., jute, hemp, sisal, banana, coir, kenaf), or animal with a protein structure (e.g., hair or wool derived from animal). Plant's fibers are basically composed by cellulose, lignin, hemicellulose, pectin, waxes, and water-soluble substances. The high presence of cellulose affects the interfacial bonding between the matrix and the fibers because cellulose is hydrophilic, while the matrix is generally hydrophobic. Interaction between vegetable fibers and composite matrix could be improved by chemical treatments (Thyavihalli Girijappa et al. 2019) with increased costs and complexity of the production process.

Animal fibers consist mainly of protein with a heterogeneous structure. Examples are silk fibers from silkworms, collagen fibers extracted from animal skins, wool fibers from sheep shearing, etc. Several studies demonstrated that among animal fibers, sheep wool suites well to building applications for both thermal and acoustic features (Klarić et al. 2020), and if used as reinforcement for adobe clay or cement mix, also for its mechanical characteristics (Alyousef R., Aldossari K., Ibrahim O., Jabr A. H., Alabduljabbar H., Mohamed A. M., Siddika A. 2019; Fantilli, Sicardi, and Dotti 2017).

When not used in the textile industry, sheep wool is an agricultural special waste produced by sheep breeding and contaminated with impurities, the type of impurity depending on the breed of sheep, the area in which the sheep are raised, and husbandry methods, with high disposal costs for breeders. Instead of being landfilled in a correct disposal way, often wool sheep is illegally disposed of with a strong environmental impact.

In Italy, according to data supply by BDN Zootechnical Register by the Ministry of Health, seven million sheep are destined to produce milk for cheese. Their wool is considered of low quality and sent to special landfills to be disposed of. Again, according to BDN data, each year more than 8,700 tons of “greasy wool” is produced. Sardinia (3,301,837), Sicily (906,069), Lazio (743,823), and Tuscany (422,734) are the regions with the largest number of sheep in Italy (Data provided by the BDN of the Zootechnical Registry established by the Ministry of Health at the CSN of the “G. Caporale” Institute of Teramo “IZS”).

Nevertheless, wool is a renewable, recyclable and environmentally friendly material, and the reuse of greasy wool could reduce both environmental pollution and energy consumption. By turning sheep wool in a new raw material, it is possible to produce innovative building materials and/or components fully complying with eco-friendly construction criteria and environmental certifications (e.g., BREEAM, LEED, DGNB, and Green Mark).

Due to their heterogeneous structure, the physical and mechanical behavior of natural fibers is difficult to predict (Yan, Chouw, and Yuan 2012). Mechanical behavior of natural fibers has been evaluated by considering its dependence on different parameters, i.e., fiber length, fiber weight ratio, fiber orientation, fabrication process. Tensile strength, stiffness, density, Young's modulus, elongation at break of some of the most common reinforcement vegetal fibers are reported in Table 1 based on data from (Latif et al. 2019; Mulenga et al. 2021). It can be observed that the values range over many orders of magnitude, but that in any case they are comparable to those of synthetic fibers (Mahir et al. 2019).

Table 1 – Mechanical properties of some common vegetable fibers

Fiber	Density [gr/cm^3]	Tensile strength [MPa]	Young's modulus [GPa]	Elongation at break [%]
Jute	1.23	325-770	37.5-55	2.5
Flax	1.38	700-1,000	60-70	2.3
Hemp	1.35	530-1,110	45	3.0
Ramie	1.44	915	23	3.7
Bamboo	1.50	575	27	2.0
Banana	1.35	721.5-910	29	2.0
Henequen	1.40	500	13.2	4.8
Pineapple	1.50	1,020-1,600	71	0.8
Kenaf	1.20	745-930	41	1.6
Coir	1.20	140.5-175	6	27.5
Sisal	1.20	460-855	15.5	8.0
Abaca	1.50	410-810	41	3.4
Cotton	1.21	250-500	6-10	7.0
Isora	1.20	550	-	5.5

Experimentally evaluated mechanical properties of natural fibers usually show very dispersed values, so that a statistical analysis is required in order to obtain valuable information for a successive mix design (Fagone et al. 2019; Zhang et al. 2002).

While wool fibers as insulating materials are usually employed in long bundles, the length of reinforcing fibers is in the range of few centimeters, depending on the type of mix they are added to. It is well accepted that shorter fibers exhibit a greater tensile strength. This is a general result, observed either with artificial and natural thin fibers, and generally attributed to the presence of flaws in the skeleton. Strength of fibers of different length can be predicted with the aid of Weibull distribution statistics, based on the theory of weakest link. The theory has proved valid for many types of natural fibers (Amoy Netto et al. 2016; Xia et al. 2009): Shao et al. applied it to bamboo fibers (Shao et al. 2013) that was also investigated by Da Inacio et al. (Inacio, Lopes, and Monteiro 2010).The latter group applied the methodology also to jute fibers (Bevitori et al. 2010). Jute has been object of much attention, due to its suitability as reinforcing material (Fagone et al. 2019; Pickering et al. 2007; Zafeiropoulos and Baillie 2007).

Xia et al. (Xia et al. 2009) apply to jute fibers a modified Weibull distribution originally proposed by Zhang et al. for accounting for the relevant geometrical irregularities met in wool fibers (Zhang et al. 2002).

The influence of fiber diameter (or, more generally, transversal dimensions) on the mechanical properties has also been widely recognized, although a general justification for it is still lacking, and the effect has been attributed to one or another physical property of the fiber.

An influence of effective diameter on mechanical properties of artificial fibers (PAN graphite fibers) was originally observed by Jones and Duncan, who attributed the effect to the sheath and core structure of the fibers, generated in the polymerization process (Jones and Duncan 1971). They argued that a thin fiber contains a larger quantity of "sheath", whilst a thick fiber contains a larger fraction of "core". The dependency of the fiber strength on the diameter is due to the preferential orientation of the crystallites contained in the sheath. A similar explanation, related to the content of cellulose in the fiber, was used by Charlet et al. for interpreting the variation of Agatha flax fiber strength with the diameter and the position within the stem (Charlet et al. 2009). On the contrary, A. Shahzad attributes the diameter effect to the possibility that the number of flaws increases in the fiber with increasing diameter (Shahzad 2013).

The hypothesis of the influence of flaws contained in the inner structures should lead to a modified form of the Weibull distribution for the tensile strength, as proposed in (Xia et al. 2009; Zhang et al. 2002).

The weakest link assumption then should correspond to a brittle fracture of protein chains once the fibrils have completely stretched. However, the result of the mechanical tests could also suggest different hypotheses, as an uneven distribution of stress in the fiber components, and a progressive type of fracture.

In this research work, an experimental campaign has been carried out with the aim of investigating a possible re-use of low-quality sheep wool. Tensile tests on almost 200 fibers were performed, and from the results the breaking tensile strength, the elongation strength and the stiffness properties, have been evaluated. Also, a new correlation is proposed between fibers' properties and fibers' diameter, usually overlooked in previous investigations.

The fibers investigated in this research work come from the shearing of "*Valle del Belice*" sheep, a domestic breed widespread in Sicily. This area of southern Italy is strongly characterized by the breeding of dairy sheep, whose fleece is not suitable for textile industry because constituted of thick and medium length fibers.

This study is the first to investigate the properties of a poor-quality wool, unsuitable for textile industry. In the past, "*Valle del Belice*" sheep wool was employed to make mattresses and pillows but currently they are only considered as a special waste with high disposal costs for farmers and the environment.

5.2 Materials and method

5.2.1 Sheep wool fiber

Sheep wool is an animal natural fiber composed of 60% animal protein fibers, 15% moisture, 10% fat, 10% sheep sweat and 5% impurities. In Table 2 is reported the typical chemical composition of wool (Parlato and Porto 2020).

Table 2 - typical chemical composition of wool

Chemical Composition of Raw Sheep Wool			
Keratin	33%	Carbon	50%
		Hydrogen	12%
		Oxygen	10%
		Nitrogen	25%
		Sulphur	3%
Dirt	26%		
Suint	28%		
Fat	12%		
Mineral water	1%		

Sheep wool has a semi-crystalline chemical structure, and is considered an α-keratin fiber, with a very complex multilayer structure. By a physical point of view SWF has a complex hierarchical structure with a predominantly α-helical conformation with microfibrils representing the crystalline part in the fiber structure, bounded by an amorphous matrix phase (Hassan and Carr 2019). In agreement with several authors (Mcneil 2015), SWF has an unique mechanical behavior determined by its structural organization of the α-keratin fibers. The principal component of SWF is a core cellular component surrounded by an outside layer with cuticle cells. This core is constituted by cortical cells organized in an overlapping manner, following the direction of the fiber axis. These cortical cells are constituted by macrofibrils, each macrofibrils being composed by several other microfibrils. Microfibrils are intermediate filaments proteins (α-keratin) bounded by keratin associated matrix proteins

(KAPs) containing high levels of sulphur and tyrosine. Microfibrils are held together by intermolecular and intramolecular interactions such as hydrogen bonds, van der Waals interactions, salt linkages and disulphide bonds. The amorphous matrix is a matrix of globules connected to each other and with microfibrils by disulphide crosslinks. The formation of disulphide bonds gives the α-helical coils rigidity increasing the stiffness of the fiber. If these disulphide bonds are broken, wool fiber works like a spring, and its dimensional stability is compromised.

Tsobkallo et al. (Tsobkallo, Aksakal, and Darvish 2012) analysed the contribution of the microfibrils and the matrix to the deformation processes of the sheep wool fibers. In their study, they also compared different research works concerning the interpretation of the structural-mechanical properties relationship of wool α-keratin fibers. They distinguished three regions in the stress-strain response: a Hookean region, a yield region, and a post-yield region. Hookean region is characterised by an almost linear increase in load whose slope is referred as Young's modulus of the material. In the yield region to a low increase in load corresponds a large elongation of the fiber. In the post yield-region the fiber stiffened again until the failure occurs.

All studies agree that Hookean region depends on stretching of the α-helix in the intermediate filaments, while the yield region derives from the unfolding of the α-helix. It is not clear in the post-yield region, the role of the fiber constituents. In literature almost all studies concern Merino Wool (Hookean region from 0 to 2% strain, yield region from 2 to 25-30%, a post-yield region beyond 30% strain) and are related to textile industry (Huson 2009). For this reason the interest was especially focused on the non-failure properties and less efforts have been spent on the breaking stress of wool (Hearle 2000). Non-textile usage of wool is not yet developed but some studies are investigating its potentialities (Alyousef et al. 2019; Bosia et al. 2015; Korjenic et al. 2015).

5.3 Experimental programme

5.3.1 Physical properties

A sample of fibers (around 180) was randomly selected among the raw material (i.e., "*Valle del Belice*" SWF), choosing fibers having roughly the same initial length (comprised between 160 and 220 mm). Each fiber, previously washed with cold water and natural soap, was dried in environment condition (T=20° C – RHU= 50%) for 1 week, and trimmed to 150 mm. The fiber diameter was measured with a Zeiss Microscope, (software LAS Core, LEICA application suite Version 3.70), taking the average of 3 measures along the length. The coefficient of variation of the fiber diameter (CV_D) along the longitudinal axis is negligible (lower than the 10%), its variation ranged between 4 to 6 μm.
Then the fibers were weighted on a precision balance Sartorius - model CP124S to obtain the density of each sample (Figure 1). Figure 2 presents a Scanning Electron Microscope (SEM) image of the wool fiber.

Figure 1- SWF diameter and mass evaluation

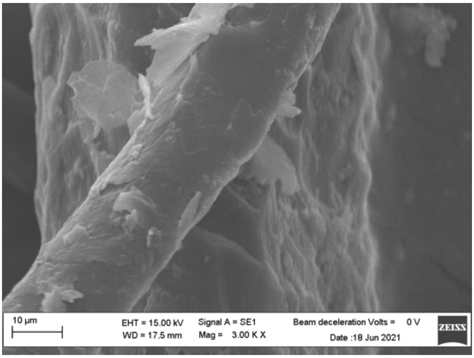


Figure 2 - SEM image of the Valle del Belice wool fiber

5.3.2 Mechanical properties

The mechanical tests were carried out on single wool fiber, following the prescription of ASTM D 2256 – 10 Standard Test Method for Tensile Properties of Yarns by the Single-Strand Method. The experimental campaign concentrated on one-gauge length only, close to the one likely to be used in the reinforcement of rammed earth prototypes. For practical reasons, a gauge length of 50 mm was selected, and kept constant. The tensile apparatus sketched in Figure 3 was designed for the tensile tests. The wool fiber was glued at the ends of the gage length between two cork clamps. The fiber assembly was placed horizontally in the apparatus to avoid the effects of gravity. One edge of the fiber was rigidly fixed to the testing apparatus, the other edge was free to slide on a Teflon sheet placed on the other side of the apparatus. The free end was connected to the loading device, applied using direct weight.

The mounting of single fiber in the tensile testing machine has been done with great care to avoid damage of the fiber, misalignment of the load, and to prevent premature failure and errors in measurement.

The selected fibers were subdivided in 3 groups of about 60 fibers each having roughly the same diameter distribution. Each group was subjected to a different conditioning program:

- 1st condition: wet condition. Fibers were immersed for ten minutes in distilled water (ten minute was found to be a sufficient time for wool to reach saturation).
- 2nd condition: controlled environment. SWF were immersed in distilled water for ten minutes, then were left to dry for 24 h in ambient with controlled temperature and humidity.
- 3rd condition: oven-dried condition. Fibers were put in oven at 80° C for thirty minutes. After this time the fibers reached constant mass.

These different test conditions were selected because the high hygroscopicity of wool. Wool can absorb large quantities of water, and experimental test results could be affected by this characteristic.

Load and elongation were directly measured during the test. An average stress was obtained dividing the load for the area of the cross section, assumed circular and using the average value of the diameter. The elongation was converted to strain by dividing for the initial gauge length. This simplification is reasonably accurate for the first part of the load displacement curve, thus allowing an estimation of the elastic stiffness.

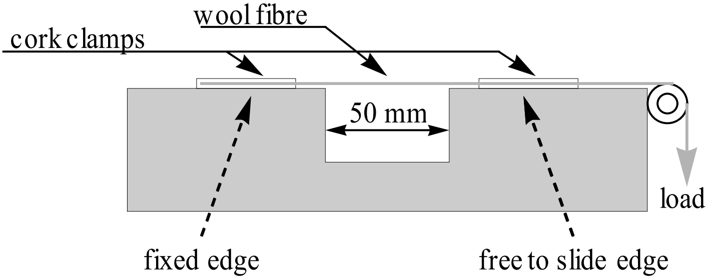


Figure 3 - Schematic representation of the load testing apparatus

Wool is a viscoelastic anisotropic material, whose tensile properties depend on the speed of application of the load (Leung and Yu 2008). In our experiments the load was slowly applied with a rate of about 2 10^{-2} N/min. Each test lasted, therefore, from 15 to 25 minutes.

The load was monotonically increased up to failure. Each test was recorded by photo images that were subsequently elaborated to get the load-elongation curve. The fiber's failure stress and strain, an estimation of the yield strength and strain and the secant initial stiffness modulus were determined from the experiment. A typical stress-strain plot is shown in Figure 4.

Four phases can be distinguished: an almost initial linear range can be recognized, from which the secant stiffness modulus can be determined. Conventionally, this was defined as the secant modulus at 60% of the yield load. Then occurs a non-linear phase, until the stress-strain curve presents a yield, after which a plateau is reached, where the stress gradient sensibly decreases. At the end of this plateau the elongation can reach a value one order of magnitude greater than the one corresponding to the yield stress. The stress and strain at the end of the plateau have been labelled σ_p, ϵ_p, respectively. Finally, the stress presents a sharp hardening; however, the last phase is not always present. Usually, breakage occurs early during this final stage.

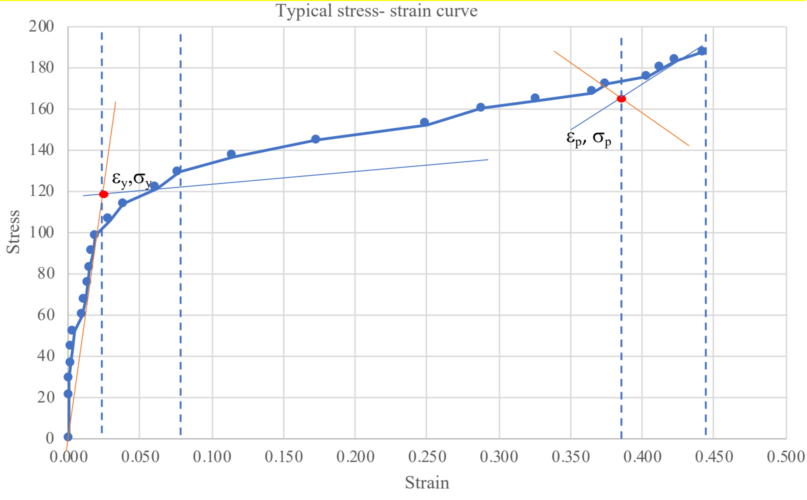


Figure 4 - Typical result of a tensile test. Fiber with 2nd conditioning setting

5.4 Results and discussion

5.4.1 Diameter and density measurements

Figure 5 shows the distribution of the values of the diameters measured for the whole population of fibers. Although most of them fall near 70 µm, the dispersion is considerable, and motivates the investigation relative to the influence of the cross-section dimension on the mechanical properties.

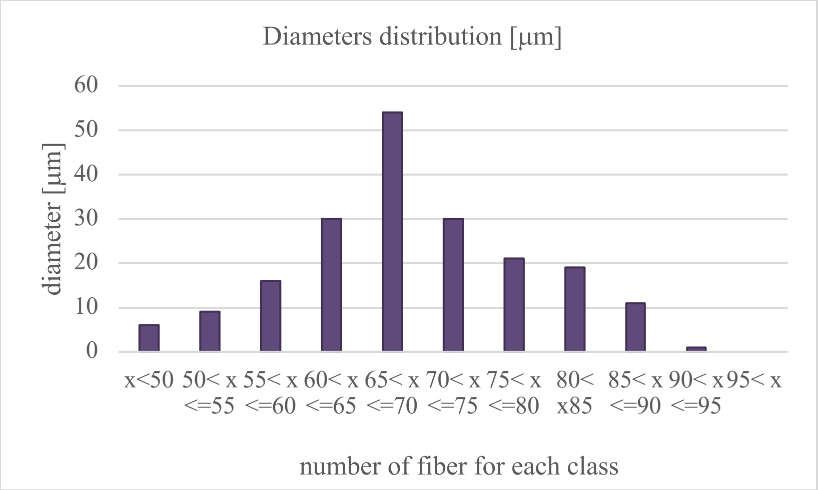


Figure 5 - Distribution of fiber diameters in the sample

Figure 6 shows that there is a marked dependence of the density on the fiber diameter: the larger the diameter, the smaller is the density. The tendency curve that interpolates the data points is compatible with a core and fibril internal structure of the fiber. The SWF average density is 0.94 [gr/cm^3] lower than synthetic fibers' density (e.g., for glass fiber it is 2.5 [gr/cm^3]), and lower than average wool density found in literature that is 1.3 [gr/cm^3].

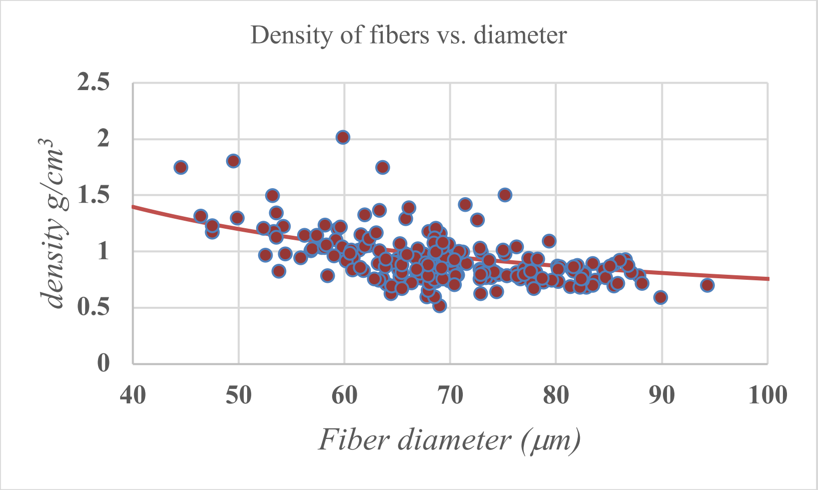


Figure 6 – Correlation between fibers density and fibers diameter

5.5 Mechanical properties

The following mechanical properties have been evaluated from each test:

- Secant Stiffness Modulus.
- Stress and strain at the yield (estimated as intersection between linearized trends in the initial phase and in the plateau region).
- Elongation at break.
- Stress at break.

Average values μ_i and standard deviations σ_i for these quantities, together with the fiber diameter, are reported in Table 4, separately for the three testing conditions and for the whole population.

Table 4 - Mechanical test results. Average values and standard deviation

	σ at break [MPa]		**Elongation at break [%]**		**σ at yield [MPa]**		**ε at yield**		**E_s [MPa]**	
	μ	**σ**	**μ**	**σ**	**μ**	**σ**	**μ**	**σ**	**μ**	**σ**
Saturated specimens	134.57	34.10	42.00	0.11	75.37	21.92	0.04	0.02	2057.06	584.53
Normal conditioning	144.02	41.61	43.00	0.11	84.70	23.31	0.05	0.02	1903.59	621.32
Dry specimens	133.65	47.22	43.00	0.19	85.97	33.59	0.07	0.03	1367.38	381.40
Entire population	137.31	41.37	42.00	0.14	81.44	27.15	0.05	0.02	1739.41	755.44

Results are quite dispersed, as typically happens with natural materials. For instance, measured breakage tensile stress ranged between 222.37 [N/mm^2] and 68.18 [N/mm^2] for saturated fibers (1st test condition), between 261.50 [N/mm^2] and 74,01 [N/mm^2] for the 2nd test condition and between 252.652 [N/mm^2] and 52.53 [N/mm^2] for the 3rd test condition.

However, the dispersion of the results is compatible with the nature of the material, and it allows to characterize its mechanical behavior with reasonable confidence, as shown in Figure 7 where all the stress-strain curves are superposed for the three testing conditions.

From the average values reported in Table 4 it can be observed that the three different test conditions do not significantly affect the results; in any case the best performances appear to be obtained for the samples with a controlled content of moisture (condition 2), which is a useful information because this is close to the real condition of fibers inside a mixture.

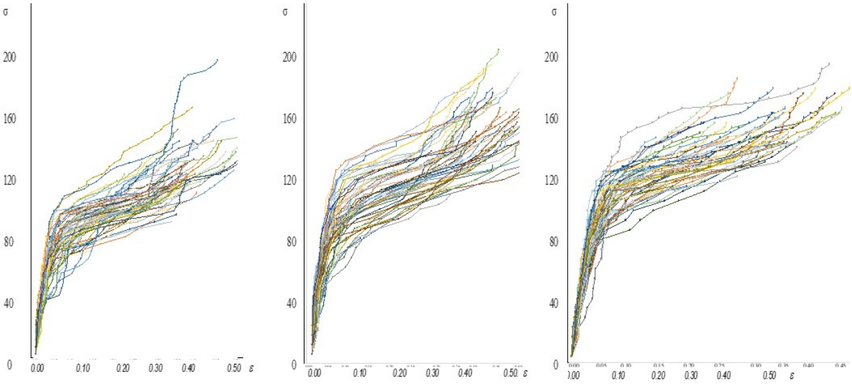


Figure 7- Stress-strain curves: (a) saturated fibers, (b) controlled environment fibers, (c) oven dried fibers

From the values reported in Table 4 can be built average trilateral stress-strain curves for the three testing conditions, joining the couples $(\sigma_y - \varepsilon_y)$, at yield, plateau stress and corresponding elongation $(\sigma_p - \varepsilon_p)$, at the end of the plateau region, and failure stress and strain $(\sigma_r - \varepsilon_r)$. The resulting plots are reported in Figure 8. This representation confirms that the thermal and hygrometric conditioning do not significantly affect the results.

By comparing our results with a typical wool tensile stress–strain curve obtained on Merino sheep, some differences can be observed. The initial linear elastic region extends up to 3-7% for "*Valle del Belice"* SWF, while the Hookean region for Merino wool usually does not exceed 2%. The yield region extends below 30% of strain in both cases. Then fracture occurs in "*Valle del Belice"* SWF between 40% and 45% of strain while the extension can reach 50% - 60% for Merino wool fibers (McKittrick et al. 2012). Consequently, also the breaking stress is larger for Merino wool.

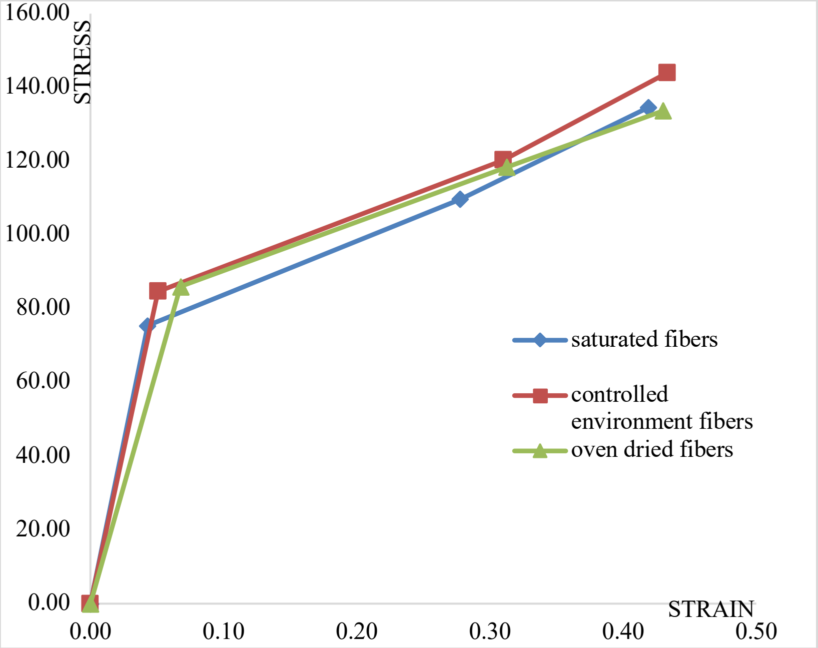


Figure 8- schematic representation of the stress- strain curve ([N/mm^2], [%]) under 3 different test conditions

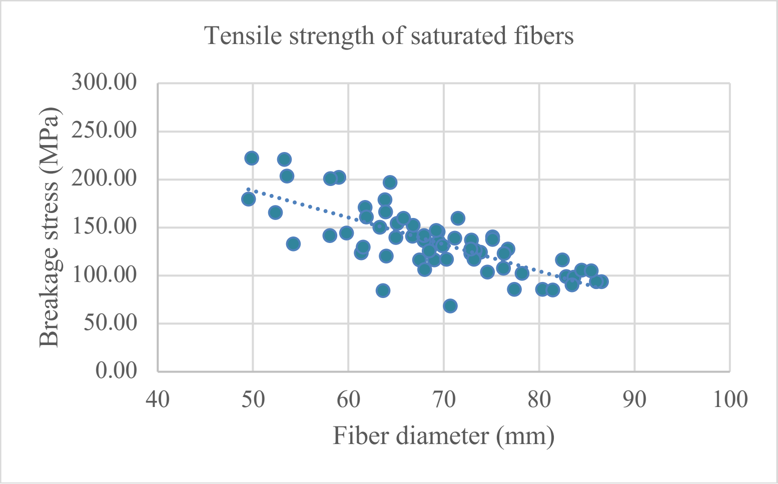
Indeed the average value of the mechanical strength found in our experiments (134 MPa) has to be compared with the value of 250 MPa (HEARLE 2002) obtained for selected wool, suitable for textile industry (e.g., Merino wool, Romney wool). The found values are instead similar to those reported by Cheung et al. (Cheung et al. 2009), where mechanical strength ranges from 120 MPa to 174 MPa.

Elongation at break, ranged between 45% and 50%, and it is comparable with literature data and higher than for other natural fiber. The results obtained, especially those relating to strength, elongation, and density, confirm the suitability of these fibers to be used as reinforcement in raw earth materials.

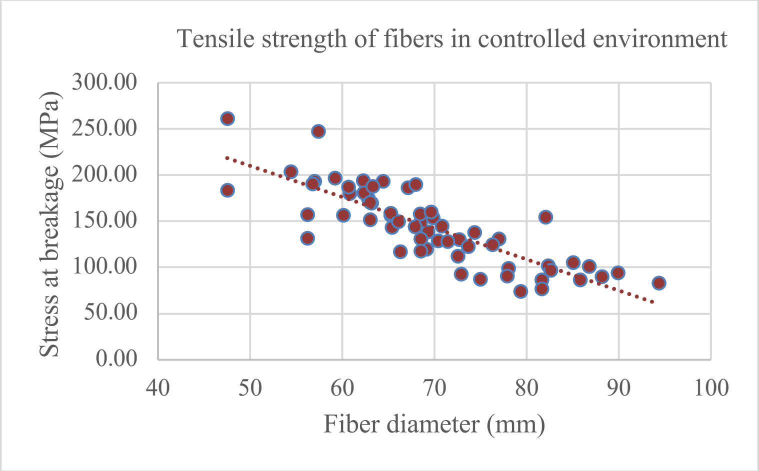
5.6 *Influence of the diameter on the mechanical properties*

The mechanical properties of fibers, especially their strength, are well known to be strongly influenced by the fiber length. The size effect can be effectively estimated with well-established methods [20]. This factor is absent in the present experimental program, since all the fibers had the same gauge length. However, it has also been reported that the mechanical properties of natural fibers change according to the fiber's diameter. In this section we aim to investigate to some deeper extent this phenomenon, that can be of some interest for optimizing the use of SWF as reinforcement material.

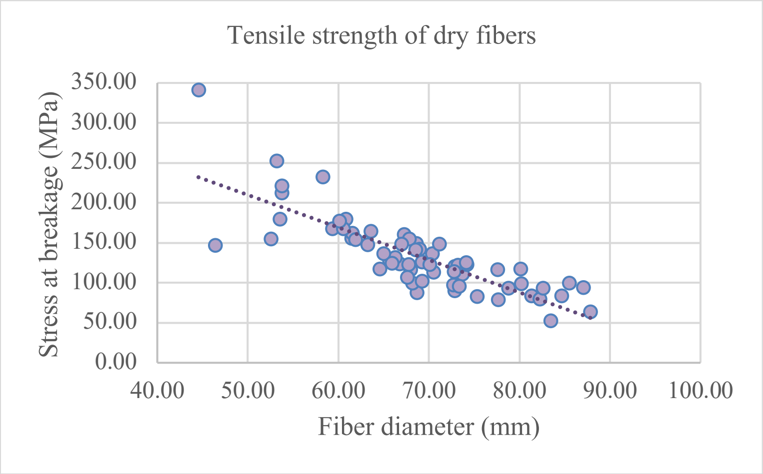
Plots of Figure 9 show the tensile strength of the three groups of fibers vs. the fiber diameter. There is a clear tendency of the breakage stress to decrease with the diameter, for all the conditioning settings, although the data present some dispersion, especially for small diameters.



(a)



(b)



(c)

Figure 9 - correlation between breakage tensile stress and diameter, (a) 1st condition, (b) 2nd second condition, (c) 3rd condition

Superposing the data, as noticed in section 3.2, there is little difference in the results obtained for the tensile strength between the three groups (Figure 10).

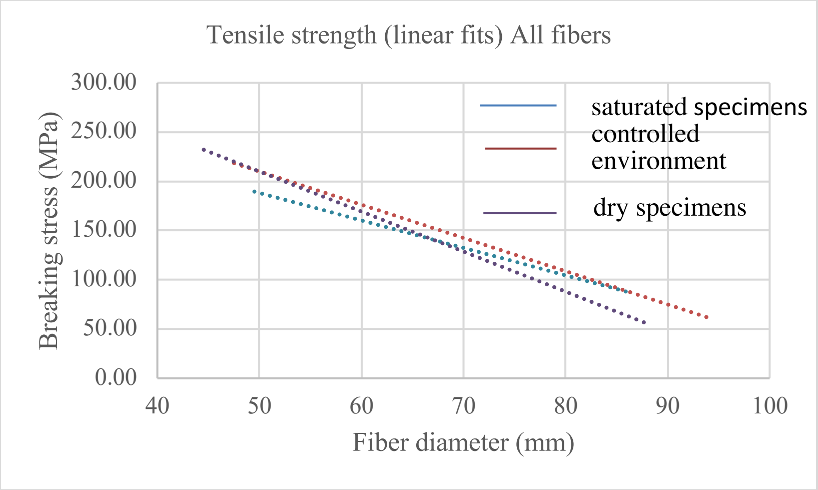
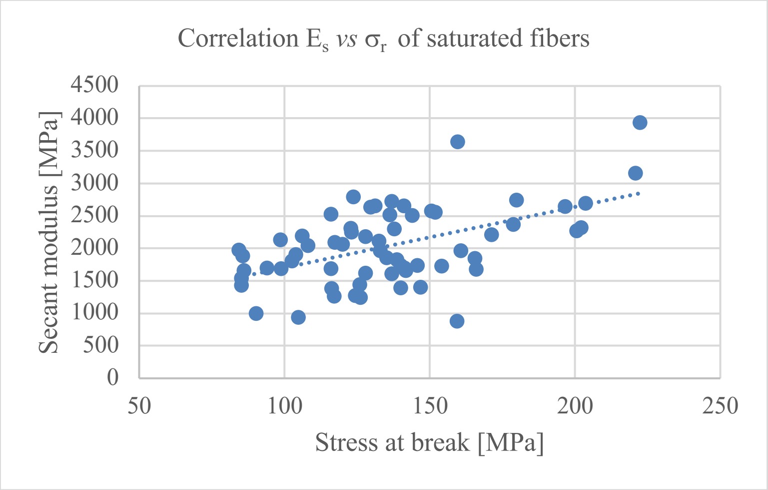
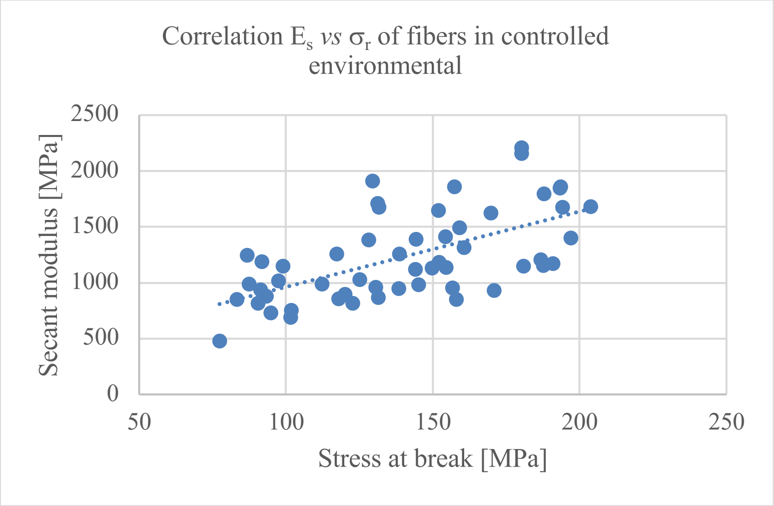


Figure 7- Correlation lines between diameter and tensile strength under the 3 test conditions

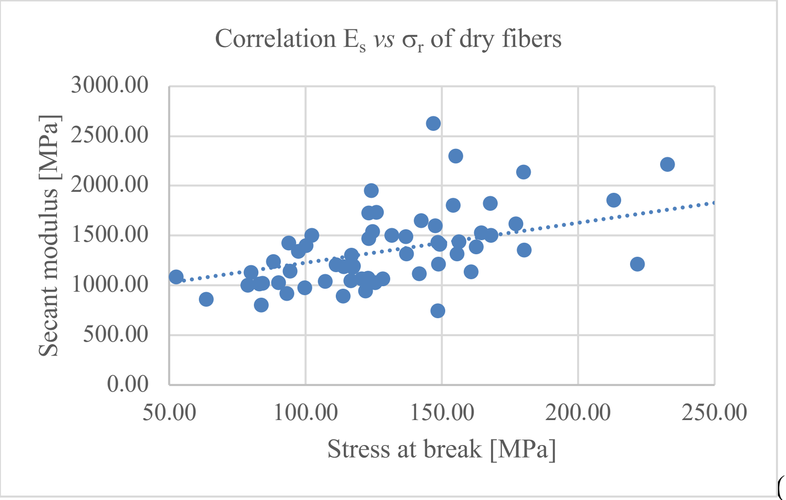
A similar dependency has been found for the other mechanical properties. The plots of Figure 11 shows that there is a direct correlation between the secant stiffness modulus (E_s) and the tensile strength (σ_r), in spite of the considerable dispersion. Consequently, an analogous correlation exists between the secant Hookean stiffness modulus and the fiber diameter (the greater the diameter the lower the stiffness).


Correlation E_s *vs* σ_r of saturated fibers
Secant modulus [MPa]
4500
4000
3500
3000
2500
2000
1500
1000
500
0
50
100
150
200
250
Stress at break [MPa]

(a)


Correlation E_s *vs* σ_r of fibers in controlled environmental
Secant modulus [MPa]
2500
2000
1500
1000
500
0
50
100
150
200
250
Stress at break [MPa]

(b)



(c)

Figure 11 - correlation between secant stiffness modulus (Es) and breakage tensile strength (σ_r), (a) 1st condition, (b) 2nd second condition, (c) 3rd condition

5.7 Statistical analysis of test results

The correlation between the mechanical properties and the fiber's diameter is interpreted using a statistical analysis based on Weibull distribution theory.

Several factors influence natural fiber tensile behavior, such as fibers' heterogeneities, chemical structure, and failure mechanism. For this reason, statistical analysis is necessary to define reliable properties of strength and stiffness of sheep wool fiber. Weibull probability distribution function is a suitable tool for the interpretation of the experimental results of specimens affected by size effects. Weibull model was conceived to correct size dependence of unidimensional structure subjected to tensile load; it considers the unidimensional structure as a chain constituted by different rings, each one having different strength, and predicts the probability of rupture of the weakest ring. Probability of rupture of the weakest rings is the probability P ($X \leq x$) that this rings fails for a force less or at least equal to x (Weibull 2021). In literature was already demonstrated that this numerical model is suitable for natural fibers included sheep wool

(Zhang et al. 2002). In this paper, a modified Weibull distribution model is proposed for considering the dependence of strength from diameter.

Weibull distribution based on the weakest link theory for the failure strength σ_f states that the probability P of failure of a fiber of volume V is

$$\mathrm{P} = 1 - \mathrm{Exp}\left[1 - \frac{\mathrm{V}}{\mathrm{V}_0}\left(\frac{\sigma_\mathrm{f}}{\sigma_{\mathrm{f0}}}\right)^{\mathrm{m}}\right] \tag{1}$$

where V_0 is the volume of a link segment, the exponent m is the Weibull modulus and σ_{f0} is a scale parameter. The value P is estimated using the probability index

$$P = \frac{i}{N+1} \tag{2}$$

where N is the total number of data points, and i is the rank of the generic data point. The two-parameters Weibull distribution was modified by Watson and Smith (Watson and Smith 1985) and Gutans and Tamuzs [41] introducing an additional parameter, in order to account for discrepancies with the experimental data. The original proposal introduces an exponent on the ratio L/L_0 assuming fibers of constant cross-section. Following this idea, in the case of fibers with different diameter we assume as probability distribution:

$$P = 1 - Exp\left[1 - \left(\frac{V}{V_0}\right)^{\bar{\gamma}}\left(\frac{\sigma_f}{\sigma_{f0}}\right)^{m}\right] \tag{3}$$

that, for the case of fibers of same gauge length, and diameter d, reduces to

$$P = 1 - Exp\left[1 - \left(\frac{d}{d_0}\right)^{\gamma}\left(\frac{\sigma_f}{\sigma_{f0}}\right)^{m}\right] \tag{4}$$

From the proposed probability distribution is possible to relate the expected strength of two fibers of diameters d_1, d_2:

$$\mu_{\sigma,2} = \mu_{s,1} \left(\frac{d_2}{d_1}\right)^{-\gamma/m} \qquad (5)$$

The experimental tensile strength values obtained on 180 SWF of different diameters were statistically analyzed by Weibull distribution. Formula (4) can be manipulated to give:

$$Ln\big(1 - Ln(1-P)\big) = \gamma\, Ln(d) + m\, Ln(\sigma_f) - \gamma\, Ln(d_0) - m\, Ln(\sigma_{f0}) \qquad (6)$$

Therefore, a plot of $Ln(1 - Ln(1-P))$ vs. $Ln(\sigma_f), Ln(d)$ should lie on a plane, the coefficients of the equation of the plane allowing to identify the constants m, γ, $Ln(d_0^{\gamma}\sigma_{f0}^{m})$.

Figure 12 shows that the data points can effectively be interpolated by a plane, whose equation yields the values

$$m = 1.27852 \qquad \gamma = -0.22606 \qquad Ln(d_0^{\gamma}\sigma_{f0}^{m}) = -4.68762$$

The correlation is quite good, the coefficient of determination being $R^2 = 0.94413$. Only some points relative to the largest diameters fall slightly outside of the plane.

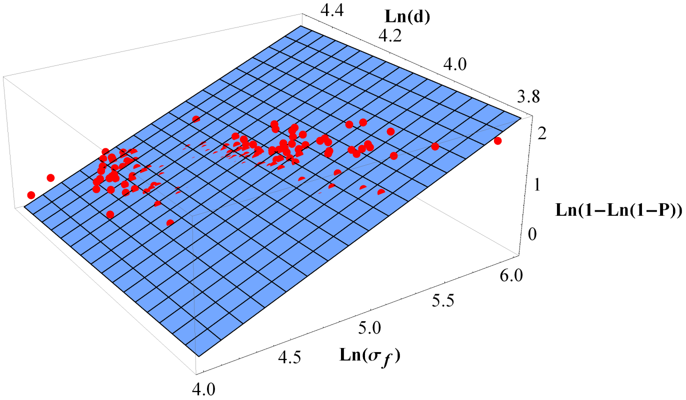


Figure 12– Interpolation of fibers' strength vs. fibers diameter

The probability density distribution of equation (4) is represented in Figure 13 as a 3D plot as function of the breaking strength and of the diameter. The data points are superposed to the plot, and closely follow the distribution function.

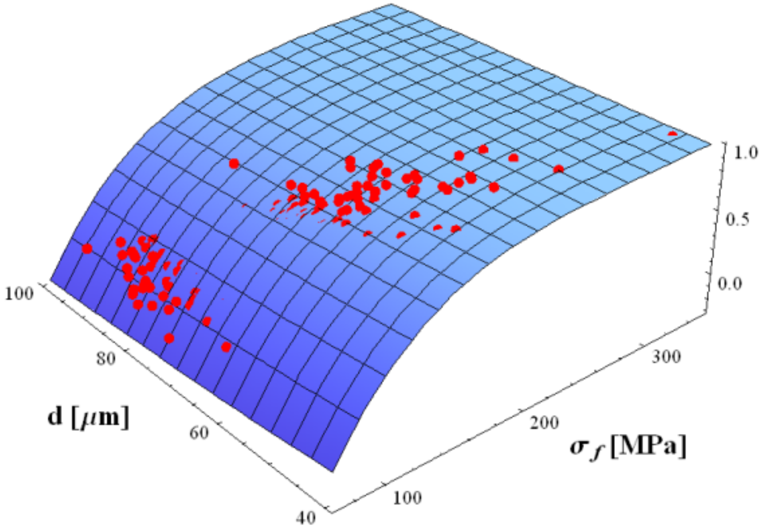


Figure 13 - Distribution function of the of fibers' strength vs. fibers diameter

From the statistical analysis, it seems that the model of distributed flaws can account for the sharp dependency found of the breaking strength on the fiber diameter.

However, further investigations are needed, in order to examine other parameters, first of all the microstructure of the fiber.

5.8 *Discussion of the results*

The values found for the strength, elongation at break, initial stiffness, are close to those reported in the literature for SWF. Compared to the properties of vegetable fibers most commonly used for reinforcement, the strength is lower, but the elongation at break is much larger. Similarly, wool fibers are less stiff than most vegetable fibers. These results suggest that the use of SWF as reinforcement in raw earth-based composites can increase their ductility and fracture energy, which is one of the main limitations in the use of those materials. Indeed, preliminary tests (that will be reported as part of a forthcoming investigation), confirm that the addition of wool fibers to raw earth mixes, together with a moderate increase in the flexural strength, allow to greatly increase the ductility of the composite.

As demonstrated, the dispersion of the results is mainly due to their dependence on the fibers' diameter. The distribution of stress at break (but also of the stress at yield) are very well fitted by Weibull statistics, suggesting that the model of distributed flaws can account for the found dependency of the fiber strength on the fiber diameter. Breakage can be due to the rupture of weak bonds connecting the layers of helicoidal fibrils, whose density is non uniform on the wool fiber, due to their hierarchical structure.

Deeper investigation is needed from a micromechanical point of view, to validate this hypothesis.

5.9 Conclusions

In this study, for the first time physical and mechanical characterization of "*Valle del Belice*" wool fibers was carried out with the aim of a possible alternative use of this agricultural special waste as strengthening system for rammed earth building components.

Tensile tests were performed on selected fibers previously subdivided in 3 groups each having the same geometric characteristics. This subdivision made it possible to study of SWF tensile performances by considering three different test settings: wet condition, controlled environment, oven-dried condition. The three groups of specimens yielded very similar results. Slightly better results have been observed for fibers tested under 2nd experimental condition, i.e., under controlled environment (SWF immersed in distilled water for ten minutes and left to dry for 24 h in ambient with temperature and humidity monitored). Since this conditioning procedure is similar to the fibers' condition inside an earth-based composite, the results obtained appear encouraging for the use of SWF as a reinforcing material.

The results found for the fibers' strength and initial stiffness are similar to those reported in literature for other types of wool, although somewhat smaller than those obtained with high quality Merino wool. An average strength of 137.31 MPa and an initial secant modulus of 1,739.41 MPa have been found, that confirm the suitability of these fibers as a reinforcement material for raw earth mixtures.

As normally occurs with natural fibers, the measured mechanical and physical properties result quite dispersed, however some trends clearly emerge. In this work fibers of the same gauge length were tested, so that the correlation between mechanical properties and fibers diameter was investigated. A statistical analysis was proposed by using a modified Weibull distribution and a very good correlation was found for the breaking stress and initial stiffness.

In conclusion, the results appear to encourage the possibility of the use of greasy wool in the building sector. This practice could decrease environmental pollution by reducing a huge amount of waste related to low-quality wool from dairy sheep also bringing benefits to the breeders.

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Conflicts of Interest: The authors declare no conflict of interest.

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6 Reuse of livestock waste for the reinforcement of rammed-earth materials: mechanical assessment *(full paper submitted to JAE in April 2022)*

Abstract

Agricultural wastes as additive within raw earth materials could both improve mechanical and physical properties of new sustainable construction materials and enhance waste management in a circular economy perspective. This study intends to fill the lack of knowledge considering the mechanical effects of animal fibers on rammed earth materials. The effects of a livestock waste, i.e., sheep wool fiber (SWF), as reinforcing element in building components produced by using raw earth and lime-free mortars, have been evaluated. Linear shrinkage, flexural strength, and compressive strength were evaluated on samples incorporating SWF, with the aim of assessing the effects of this waste addition on the mechanical performances of a new bio-composite material. The samples were made by varying the content of wool (0.25 % or 0.50% weight) and the length of the fibers (from 10 mm to 40 mm). The best result of the flexural strength was 1.06 MPa, exhibited by samples made with the longest and highest percentage of fibers, 40 mm and 0.50%, respectively. The compression strength was not affected by the addition of fibers and the value was about 3.00 MPa.

***Keywords**: building sustainability, raw earth materials, livestock wastes, natural fibres, sheep wool, mechanical behavior.*

6.1 Introduction

Today, the construction sector, is the leading cause of environmental degradation, global warming, and climate change, with 50% of carbon emissions, 20% to 50% of energy and natural resource consumption, and 50% of the total production of solid waste (Vasilca et al. 2021). For this reason, the interest of researchers and technicians in new alternative construction materials derived from renewable sources is growing constantly (Bonoli, Zanni, and Serrano-Bernardo 2021). Sustainability and energy efficiency of buildings are based on thermal insulation qualities, energy demand, and low CO_2 emissions; the use of alternative eco-friendly materials, recyclables, renewables with a low footprint impact could contribute to achieve a sustainable building sector.

In this context, the interest in earthen construction materials is increasing both for the restoration of existing historical and cultural built heritage and new constructions. Several advantages come from the use of raw earth-based materials, all related to a significant decrease in environmental pollution and CO_2 emissions. Raw earth building components, if made without chemical additives (i.e., only by physical and mechanical stabilization), are totally recyclable (Achenza and Sanna 2009; M. Parlato, Porto, and Cascone 2021). Generally, raw earth-based building components are extracted and worked directly or close to the building site, so their use significantly reduces logistic and transportation costs and the related gas emissions. Compared to common building materials (i.e., concrete, steel, glass) raw earth-based materials are suitable to balance and control indoor acoustic and thermal comfort (Fagone et al. 2019). In fact, they could control internal temperature variation, especially in the case of high temperature, because of their thermal mass, humidity absorption/desorption rate, and heat storage power.

The weaknesses of raw earth-based materials are low resistance to rain action, low flexural strength, low ductility, and high shrinkage (Medvey and Dobszay 2020; Sangma and Tripura 2020). Shrinkage is a physical phenomenon that occurs during the drying period and that produces significant crack development on the surface and/or the internal material (Sangma and Tripura 2020). To solve these negative characteristics, additives or stabilizers are often used to design raw mixes, such as mineral binders (cement, alginate, bitumen) (Rivera-Gómez and Galán-Marín 2017; Turco et al. 2021), animal and vegetal stabilizers (oil, casein, animal glue, latex) (Medvey and Dobszay 2020), reinforcement fibers, synthetics, or natural (Eliche-Quesada et al. 2017; Ramesh 2016). Recently, several studies have focused their attention on Agricultural Waste (AW) and their high potential use in different construction applications, all with the aim of minimizing their production and promoting environmental sustainability (Barreca et al. 2019; Reif, Zach, and Hroudová 2016; Liuzzi, Sanarica, and Stefanizzi 2017). When considering their significant mechanical and physics performances, AW are suitable as alternative materials in the building sector and are considered the most sustainable, economical, and energy efficient resources (Jannat et al. 2020).

Some types of agricultural waste, such as vegetable fibers, coconut shell, palm oil clinkers, and rice husk ash, are already being used as alternative materials in the construction sector. For example, coconut shell is used as a lightweight aggregate in the construction of flooring tiles (Ahmad and Kassim 2019).

Many scientists have evaluated the use of AW as natural additives in the field of unfired earth materials (Vatani Oskouei, Afzali, and Madadipour 2017; Serrano, Barreneche, and Cabeza 2016; Araya-Letelier et al. 2018). These studies focused mainly on agro-waste fibers (e.g., straw fibers, Hibiscus cannabinus fibers, ground olive stones, wheat straw fibers) (Salih, Osofero, and Imbabi 2020). The main advantage of fiber reinforcement is to improve the mechanical properties, shrinkage rate, and ductility of the composite (Laborel-Préneron et al. 2016). Serrano et al. investigated four agricultural by-products, i.e. corn plant, fescue, straw, and ground olive stones, as additives in adobe bricks to study the variability of mechanical properties and evaluate ideal formulations (Serrano, Barreneche, and Cabeza 2016).

Ashour et al. (Ashour et al. 2015) investigated the stabilization of a soil by using natural wheat and barley straw fibers to generate unfired reinforced bricks with high thermal and static qualities. The effect of the incorporation of straw fibers on the mechanical properties of unfired earth bricks was also emphasized by Vega et al. (Vega et al. 2011), and by Parisi et al. (Parisi et al. 2015).

In the literature, most studies are related to the addition of vegetable fibers to rammed earth, and fewer researchers have evaluated the mechanical effects of reinforcements of animal fibers (eg., pig hair, sheep wool) (Araya-Letelier et al. 2018; Statuto, Sica, and Picuno 2018).

In Europe in 2011, the estimated production of raw sheep wool based on sheep number was about 260,000 tons. In Italy, the estimated annual production of raw wool is around 14,000 tons, of which only a small part, around 5%, is suitable for the textile industry and has a commercial value (Rajabinejad, Bucişcanu, and Maier 2019). A large amount of raw sheep wool that is not suitable for the market represents for sheep farmers a relevant issue due to the complexity and difficulty of the disposal management. Moreover, the increasing waste landfill fees is often the main reason of the illegal disposal of raw sheep wool (Saxena and Sewak 2016). In accordance with European Environmental Regulations (EC Regulation 1069 (2009), EU Regulation 142 (2011)), raw sheep wool must be sent to specialized sites for incineration or landfill, and only if it is previously washed or disinfected, it can be buried or burned without a permit. Due to the increasing interest of researchers and economic actors for sustainable use of natural resources, raw sheep wool was reconsidered as a renewable resource by converting a difficult waste into a value-added material. The valorization of this livestock waste, the complex disposal, as components of building elements, is in turn sustainable both from the point of view of reducing CO_2 emissions in the production process and of reducing energy costs for managing the construction. Wool is a renewable, recyclable, and environmentally friendly material. Reusing greasy wool is of significant interest for sustainable development, for valorising local building materials, and for reducing a large amount of waste, especially in rural areas. Wool fibers are used as thermal and acoustical insulation of buildings, as reinforcement fiber for composite materials, as sorbent materials for the treatment of water pollution, etc. (Dénes, Florea, and Manea 2019).

This study refers to the possible reuse of raw sheep wool, trying to partially fill the lack of knowledge about the effects of animal fiber reinforcement on rammed earth materials.

The use of vegetable fibers (much fewer animal fibers), both as insulating and reinforcing element, has been extensively investigated especially in traditional construction (i.e., adobe bricks, earthen and bamboo walls, etc.) (Van Vuure et al. 2015; Abdul Khalil et al. 2012).

In this paper, the use of short wool fibers as reinforcing elements of structural and non-structural building components is proposed in combination with eco-sustainable materials such as raw earth and lime-free mortars. The research gap that this paper attempts to address and, therefore, the novelty of the study, lies in the combination of animal fibers with binders that do not use cement or lime to reduce the impact resulting from the production processes. In addition, results involve comprehensive examination through cross comparison of mechanical performance to obtain in-depth information with the goal to propose these new materials as an alternative to other more common earthen products reinforced with plant fibers. The attempt is to evaluate the consequences of the addition of this waste to unfired materials made with clay soil present in Sicily, which was formerly used to produce bricks, and added with pyroclastic sand. This pyroclastic sand is typical of the Etna volcano area located in Sicily (Italy) and is commonly used to increase the mechanical strength in mortar and concrete products. The design of the raw earth mix was prepared by performing only a physical stabilization, without the use of chemical additives, by obtaining a material that is totally recyclable at the end of its useful life. The elements that we propose to develop could be both closing elements and structural elements. The latter could be made in situ by using advanced 3D printing techniques for civil engineering (Perrot et al. 2018), for which further experiments occur, especially on the fluidity property of the material. From the point of view of the development of the building chain, the possibility of creating components with effective insulating power at low cost, using non-polluting materials such as earth and wool fibers, responds to the need to improve the energy efficiency of buildings (Abdou et al. 2021) with limited impact on construction and management costs. Experimental tests on the physical and mechanical behavior of raw earth-based materials were reported under flexural and compression tests. Since the mechanical behaviors of the raw earth building components are sensitive to both soil composition and fiber content, the length and percentage of the SWF were changed to evaluate the best mix design. According to the results obtained, the reinforcement by fibers is essential to confer the due ductility to the bio-compound. First, test samples were performed by using the same soil mix design and varying only the fiber content (0,25% or 0,50%) and the length of the fibers (from shorter fibers of 10 mm to longer fibers of 40 mm). Six different repetitions were performed. Then, physical, and mechanical tests were carried out to obtain dry density, compressive strength, flexural rate, and shrinkage rate. Moreover, considerations have been made concerning the failure mode.

Finally, the results have been compared with those of other studies that investigated other agricultural waste additives.

6.2 Materials and method

6.3 Clayey Soil and Volcanic Sand

Experimental tests were carried out on a soil mix previously investigated by authors (M. Parlato, Porto, and Cascone 2021); this soil, choose among five different soil design for its best performances, was embedded with raw sheep wool. The base material is composed of kaolinite soil called terra *di Floridia* (FS) (extracted close to Syracuse in Sicily and traditionally used to produce bricks) modified through a physical stabilization process (Achenza and Sanna 2009).

To obtain the mix used in this work, the original particle size distribution of the soil of "*terra di Floridia"* was changed by adding clay, according to a ratio of 58% FS soil to 42% clay, in weight, by obtaining a modified FS (FS^M).

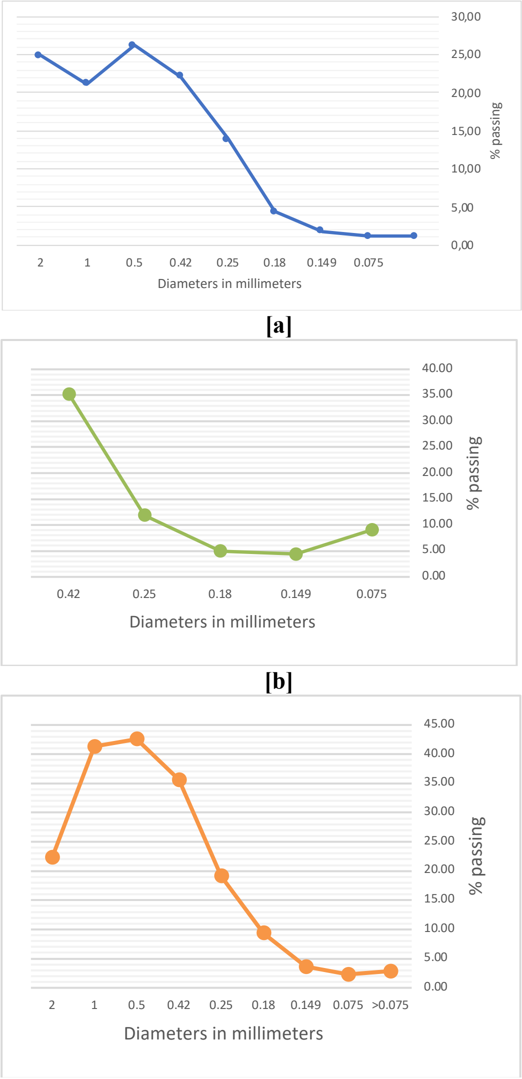
The clay used for the stabilization process comes from a pit located near Misterbianco, in the province of Catania (Italy). The basic components used for the casting of the samples were chosen for their chemical and mechanical properties and favoring local materials with a consequent reduction in logistic and transport costs. Subsequently, to improve its mechanical resistance, the modified '*Terra di Floridia*' (FS^M) has been mixed with a typical pyroclastic sand of the Etna volcano area (Sicily) and commonly used to produce mortars and concretes. This characteristic sand called ‘azolo’ is formed on the surface of the lava by crushing glassy materials generated by rapid cooling of the magma. Table 5 shows the chemical composition of clay and volcanic sand added to FS.

Table 5-chemical composition of clay and volcanic sand

Chemical Components	**Clay [%]**	**Volcanic Sand [%]**
SiO_2	53,15	45,9
Al_2O_3	14,42	20,43
TiO_2	0,85	1,44
Fe_2O_3	6,09	9,99
MnO	0,10	0,15
MgO	2,13	4,71
CaO	7,21	10,22
Na_2O	1,17	4,02
K_2O	2,08	1,35
S	0,03	-
P_2O_5	0,16	0,48

Ciancio et al. stated that the particle size distribution (PSD) is a tool that allows assessing whether a soil is suitable for earth construction, although in the literature a discordant proportion of clay, silt, sand, and eventually gravel are suggested for raw earth buildings (Ciancio, Jaquin, and Walker 2013).

Sieve analyses were carried out in an earlier study (M. Parlato, Porto, and Cascone 2021) according to ASTM D7928 – 17 requirements in order to determine the particle size distributions of FS and clay (Figure 1a, b). In Figure 1 c, the expected particle size distribution of FS^M is reported.



[a]

[b]

[c]

Figure 1- Particle size distribution of Floridia soil (FS) [a], Clay [b], expected size distribution of FS^M [c]

In Table 6 are shown the Atterberg limits of FS evaluated by Giuffrida et al. (Giuffrida, Caponetto, and Cuomo 2019), by performing the plasticity test to obtain the liquid limit (LL), the plastic limit (PL), and the plasticity index (PI= LL - PL).

Table 6 Atterberg limits of terra di Floridia soil (FS) (Giuffrida, Caponetto, and Cuomo 2019)

LL (%)	PL (%)	PI (%)
47,30	30,68%,	16,62

6.3.1 Livestock waste as reinforcement fibres: sheep wool

The livestock waste used in this investigation is typical raw wool from Sicilian sheep of the '*Valle del Belice'* race, widespread in this region, whose fleece, thick and medium length, is rejected by the textile industry. In the recent past, these fibers were suitable for mattress and/or pillow production, but currently they are only considered special waste with high disposal costs for breeders.

Moreover, sheep wool fibers are suitable for restoration of traditional buildings, diffused in rural areas, because the sheep wool composition blends with the original mortar (M. C. M. Parlato and Porto 2020).

Therefore, to improve sustainability and reduce environmental pollution, by reducing a large amount of waste, the reuse of greasy wool in the building sector could become a great opportunity. Sheep wool fibers used as reinforcement fibers, that is, '*Valle del Belice*' fleece, is a very coarse wool, with diameter ranged around 70.0 μm. These fibers were physically and mechanically characterized by the authors in a recent study. The percentage of fibers used in the mix ranged between 0,25 % and 0,50 %, in weight. This low percentage in weight corresponds to a large volume of fibers due to the low density of this kind of wool (average density of 0.94 gr/cm^3).

The length of the fibers varies between 10 - 40 mm, to evaluate the possible effects caused by the different lengths on the mechanical behaviours of the samples. Moreover, longer fibres could be an impediment for future use of this material in advanced 3D printing techniques.

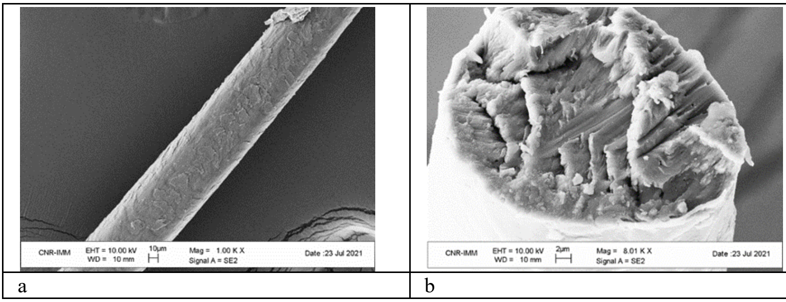
6.3.2 Study of wool fibre mechanical behaviors

In this work, a livestock waste material has been integrated on raw earth samples. The waste used is raw sheep wool, deriving from sheep breeder sector and belonging to the "*valle del Belice*" race highly widespread in Sicily. Its fleece, thick and medium length, is totally unsuitable for textile industry. By current European Environmental Regulations (EC Regulation 1069 (2009), EU Regulation 142 (2011)), wool is an animal by-product (ABPs) requiring specific procedures for handling, treating and disposal, and transportation; this means high disposal costs for breeders.

The valorisation of this (ABPs) could contribute to decrease environmental pollution by the reduction of a huge amount of waste by becoming an economic benefit for breeder.

In a previous study (M. C. M. Parlato, Cuomo, and Porto 2022), a sample of this kind of wool, constituted by 180 fibres randomly selected, was deeply characterized by authors. With the aim to assess the behaviours of this raw sheep wool and its potential use as reinforcement fibre in raw earth materials, its physical and mechanical performances have been assessed.

The obtained results encouraged the use of SWF as reinforcing material: 137.31 [MPa] is the average tensile strength found, elongation at break determined was of 42.00 %. In Figure 2 a and b are shown the surface and the transversal section of one single *valle del Belice* fiber.



a b

Figure 2 – SEM analysis of sheep wool fibre surface (a) and transversal section (b)

6.4 Adobe mix samples preparation

The preparation of the samples began with the addition of fibers to the homogeneous soil mix, that is, FS^M and sand (Figure 3). All specimen's preparation and compaction process have been executed manually. SWFs were slowly and carefully added to the clay soil to reduce the formation of fiber bundles. In the end, once the fibers were fully incorporated into the mixes, water was added in four steps, manually stirring between each step. The samples were cast in consecutive layers and compacted by hand applying sufficient pressure. Three days after casting, the samples were demolded and kept in an open space in dry conditions for 28 days to cure before testing. A similar curing procedure is in accordance with the New Zealand Code (NZA 4298 1998) and was used in previous research, also with non-cement stabilized earth samples (M. Parlato, Porto, and Cascone 2021). After curing time, the weights and dimensions of each sample were measured, and then the densities were evaluated.

Figure 3 – mix preparation, and addition of SWF into the mix

As stated above, to perform a sensitivity analysis on the impact of different fiber lengths and dosages on the performance of adobe mixes, SWF was cut in length (from 10 mm to 40 mm) and mixed in dry soil at a 0.25% or 0.50% per dry weight of soil.

6.5 Mechanical and physical performances

6.5.1 Flexural and Compressive test

According to European standards (EN 1015-11:2019) for the mechanical testing of moulded mortar specimens, prismatic samples (160 mm × 40 mm × 40 mm) were prepared. To prevent adherence, the standard steel molds used were previously moistened.

Nine different combinations of mixes, named and listed in Table , with six repetitions for each mix, were tested to assess the influence of SWF addition on the design of the adobe mix. The samples were manufactured by changing both the length and percentage of fiber. As stated before, the base soil used is a blend of FS^M and sand (*azolo*).

Table 3- Sample composition used for mechanical tests

Mechanical tests			
Specimen's type	**Test Purpose**	**Number of mixes**	**Number of specimens**
Prismatic (160x40x40)	Flexural Strenght Compressive Strength Linear Shrinkage	9	54

Table 5 - ID specimen and mix design

Mix	Wool lenght [mm]	Wool [%]	Soil [%]	Water [%]
ID - 0	-	-	80	20
ID 10 -25	10	0.25	79.75	20
ID 10 - 50	10	0.50	79.50	20
ID 20 - 25	20	0.25	79.75	20
ID 20 - 50	20	0.50	79.50	20
ID 30 - 25	30	0.25	79.50	20
ID 30 - 50	30	0.50	79.50	20
ID 40 - 25	40	0.25	79.75	20
ID 40 - 50	40	0.50	79.50	20

First, mechanical assessment began with the flexural tests. Using a Universal Testing Machine (UTM) connected with a Load Cell Hottinger Baldwin performed the test; Catman Software for Tests with Huge Channel Counts implemented data acquisition. Applying a single point load at the mid-span performed flexural tests, the speed of load was 10 N/s. Load values were recorded from the start until the sample failure. The Prismatic specimens were placed on two lower roller supports (100 mm wheelbase). By using *Equation 1* the flexural strength of specimen (σ_f) was evaluated.

$$\sigma_f = \frac{3\,F\,L}{2\,b\,d^2} \qquad (1)$$

where F is the maximum applied load, L is the span between supports (100 *mm*), b is the width of the specimen at the mid-section and d is the average depth of the specimen at the fracture section.
After failure was performed the compressive test on the two remaining prismatic parts obtained after the flexural fracture. These samples kept the same flexural ID by adding number 1 or 2.

To determine compressive strength value (σ_c) *Equation 2* was apply:

$$\sigma_c = \frac{F}{S} \qquad (2)$$

where F is the maximum applied load and S is the surface of the loaded section. In both case of flexural and compressive test, the breaking loads were determined in correspondence to the maximum load reached during the tests.

6.5.2 Linear Shrinkage

Shrinkage is a physical phenomenon that refers to the drying process of the soil mixture caused by evaporation of moisture content; it determines the cracking of the material, which can increase the penetration of water, loss of strength, and material decay (Sangma and Tripura 2020).

The Linear Shrinkage Test is a suitable tool for obtaining information about the shrinkage behavior of raw earth materials, especially structural components to correctly anticipate the joint design of space construction (Ciancio, Jaquin, and Walker 2013). The requirements for the maximum shrinkage of rammed earth are identified, although the threshold values are discordant, for example the New Zealand Standard (NZA 4298 1998) is 0.05% and the German Lehmbau Regeln (Volhard 2009) 2%. After 28 days, the shrinkage was completed, and linear shrinkage was measured in the specimens evaluating the effects of reinforcement fibers. In accordance to testing method ASTM C326-09 suitable for earthen materials, the linear drying shrinkage (*Sd*) is calculated by using Equation 3:

$$Sd = \frac{Lo-L}{Lo} \times 100 \qquad (3)$$

where L is drying length of specimen, measured by using a calibre, and L_0 is the internal length of mould.

6.6 Results and discussion

6.6.1 Effect of sheep wool addition on Flexural and Compression strenghts

Figure shows the average values and error bars (standard deviation above and below the average) of the flexural strength of each adobe mix tested 28 days after casting. As usually happens with natural materials, the results are quite dispersed with average values of flexural strength ranging from 1.06 and 0.50 MPa.

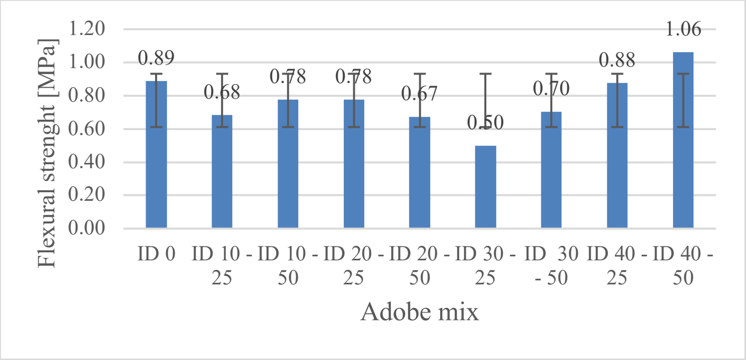


Figure 4 - Average values of flexural strength of adobe mix

The results obtained showed a reduction in the average flexural strength of the reinforced samples, with values ranging from 1.12% (ID 40 – 25 with 0.88 MPa) to 43% (ID 30-25 with 0.50 MPa) compared to the unreinforced samples (0.89 MPa). Other research works (Araya-Letelier et al. 2018; Baeza et al. 2013) have already observed the same trend and ascribe this negative effect of cluster formation inside the mix that avoids complete adhesion between fibers and the raw matrix. On the contrary, samples made with mix ID 40-50 obtained higher values of flexural strength (1.06 MPa) because an increase in the length of the fibers determines an increase in the flexural strength.

In any case, all adobe mixes exhibited an average flexural strength higher than the limit required by the worldwide used raw earth regulations, e.g., the New Mexico Earthen Building Materials Code, that foreseen an average minimum flexural strength of 0.35 MPa.

The mode of failure observed under compression tests was characterized by the gradual formation of diagonal cracks on the lateral sides of the samples without an immediate failure after the peak load, as expected for specimens realized without fiber addition. The natural fibers held together significant parts of the soil matrix by delaying failure. Additionally, there was no rupture of the sheep fibers, although a loss of bond between the fibers and the soil matrix was recorded in the proximity of the cracks (Figure 5).

Figure 5 - Wool specimens after compression test.

In Figure 6 the average values and error bars (one standard deviation above and below the average) of the compressive strength of each tested adobe mix are reported. The compressive strength values are homogeneous with respect to flexural strength value, with average compressive strength values ranging from 2.58 MPa to 3.67 MPa, expect for specimens made with mix ID 30 -25 that obtained a value of 1.42 MPa.

Analyzing these results appears that addition of fibers in the mix does not affect the compressive strength. The addition of fibers to the mix determined an increase in the average compressive strength ranging between 3% (ID 10-25, ID 10-25 and ID 20-50) and 20% (ID 10-50). ID 40-50 registered an increase in compressive strength of the 55. A reduction of compressive strength of 46% for ID30-25 and 16% for ID 30 -50.

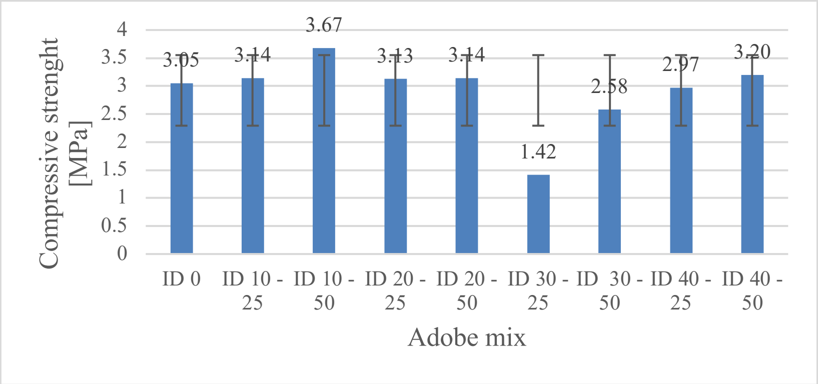


Figure 6 - Average values of compression strength of the adobe mix.

In Table 4 are shown mechanical results concerning the adobe mix tested in this study, included the dry density, are summarized.

Table 4 – Average flexural and compressive strength with correlated standard deviation.

Mix	Fibre lenght [mm]	Wool Percentage [%]	Average Flexural strenght [Mpa]		Average Compression strenght [Mpa]		Dry density [kg/m³]
			σ	μ	σ	μ	
ID - 0	-	-	0.89	0.18	3.05	0.43	1960.0
ID 10 -25	10	0.25	0.68	0.16	3.14	0.29	1904.3
ID 10 - 50	10	0.50	0.78	0.16	3.67	0.63	1904.4
ID 20 - 25	20	0.25	0.78	0.17	3.13	0.35	1890.0
ID 20 - 50	20	0.50	0.67	0.23	3.14	0.62	1841.3
ID 30 - 25	30	0.25	0.50	0.20	1.42	0.13	1678.0
ID 30 - 50	30	0.50	0.70	0.19	2.58	0.47	1844.5
ID 40 - 25	40	0.25	0.88	0.19	2.97	0.35	1844.5
ID 40 - 50	40	0.50	1.06	0.20	3.20	0.40	1883.0

Numerous studies have evaluated the mechanical performance of cementitious composites, including wool fibers; however, only a few studies have been carried out to investigate the mechanical effects deriving from the addition of wool fibers in raw earth materials.

The values obtained for the mechanical properties of the unfired adobe considered in this study compare well with those reported in other scientific papers on similar fibers. Galan et al. (2010), investigated the effect of adding sheep wool and alginate to raw-earth-based specimens. The reported values were 1.10 MPa and 3.05 MPa for flexural and compressive strength, respectively (Galán-Marín, Rivera-Gómez, and Petric-Gray 2010).

Statuto et al. (2018) evaluated the compressive strength of clay adobe brick reinforced by sheep wool fibers. They found that clay bricks mixed with 3% by weight of sheep wool exhibited an average compressive strength of 4.32 [MPa] (Statuto, Sica, and Picuno 2018). Araya et al. (2018) in their study addressed the use of a massive food industry waste, i.e., pig fibers, as reinforcement in raw-earth adobe mixes. The results obtained for adobe which incorporated 0.5% of 30 mm length fibers were 0.34 MPa for flexural strength and 1.49 MPa for compressive strength (Araya-Letelier et al. 2018).

The correlation between dry density and average compressive strength has been investigated; the correlaction factor (R^2) found is 0.74: the higher the density, the higher the compressive strength obtained by performing the test. The compressive strength of the adobes increases consistently as the dry density increases (Figure 8Figure 8).

This is in contrast with Ciancio et al. (2013) that stated that the correlation between dry density and strength for unstabilised samples cannot be proven (Ciancio, Jaquin, and Walker 2013).

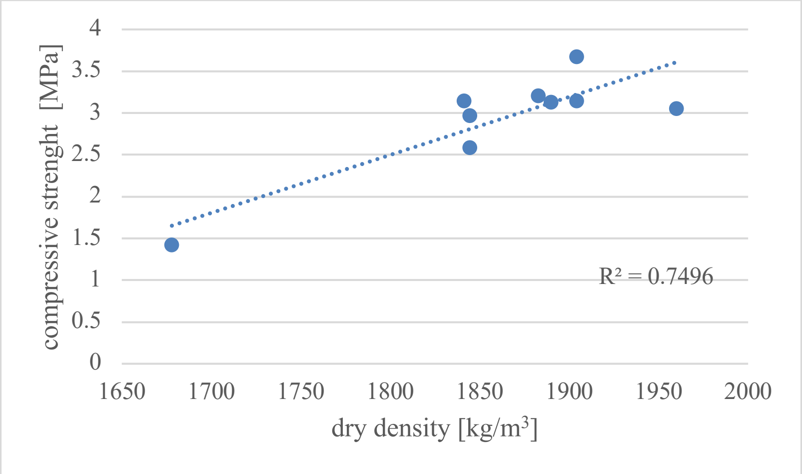


Figure 8 – correlation among dry density and compressive strength

In general, the direct correlation between density and compressive strength is widely accepted.

When additives are introduced into the mix, a quantity of soil is replaced by them. Depending on the lightweight of the material added in the earth mixture, the final blocks will have a lower density. Additives, that is, natural fibers, increase porosity, influencing the shape and geometry of pores [40] by decreasing density. For this reason, several studies recommended not exceeding a certain threshold that could result in excessive pore presence (Turco et al. 2021).

6.7 Effects of fibre addition on Linear Shrinkage

The linear shrinkage rate for the specimens concerning the different adobe mixes was evaluated by applying Equation 3. Samples made with soil mix ID 0 exhibited the highest shrinkage rate, corresponding to 6.25%. Specimens made with soil mix ID 30-25 exhibited the lower shrinkage rate of 3.33%.

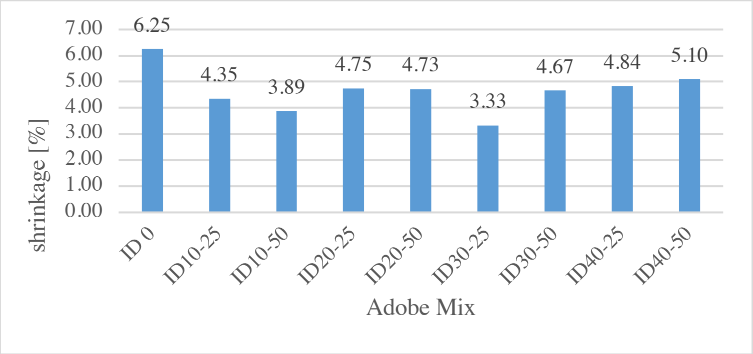


Figure 9 – shrinkage rate for prismatic specimens

The general trend is that addition of fibres in the mix cause a shrinkage rate decreases, as already demonstrated in other researches with comparative analysis among reinforced and unreinforced samples (Vega et al., 2011) (Figure 8). Nevertheless, all linear shrinkage rates are higher than the 2 % rate, that is the maximum rate admitted by standard requirements as German standard (Volhard, 2009), and Australian standard ("Australian Earth Building," n.d.). The general trend is that the addition of fibers to the mix causes a decrease in the shrinkage rate, as already demonstrated in other research with comparative analysis among reinforced and unreinforced samples (Vega et al. 2011) (Figure 9).

6.8 Conclusions

The agricultural sector produces a huge amount of waste, by-products, and co-products, whose disposal constitutes a serious financial and ecological concern.

This work assessed the effectiveness of incorporating a livestock waste, sheep wool fiber, as a reinforcement fiber in raw earth specimens. The purpose was to valorise local building materials and contemporary reduce a huge quantity of waste, especially in rural areas, where they are products.

In fact, the reuse of agricultural waste could represent a good alternative for the construction sector, increase income and valuable employment opportunities, develop rural areas, and reduce the problem of environmental pollution.

The mechanical tests performed in this study given some information concerning the best length fibers and percentage to be used in reinforced adobes.

By analyzing obtained results:

- Flexural strengths reach the higher value of 1.06 MPa when length and concentration of fibers increase (ID 40-50), respect the non-fibrous samples; the reason could be the higher contact surface between fibers and clay matrix according to previous studies.
- Compression strengths are not affected by fiber addition, with almost all values ranging around 3.00 MPa.
- Linear shrinkage decreases by fiber addition (from ID 0 with 6.25 % to the minimum rate of ID 10-50 of 3.89%, not considering ID 30-50).
- The addition of fibers to the mix determines the decrease of dry density from 1960.0 [kg/m^3] to 1850.00 [kg/m^3], not considering ID 30-50.

- All mechanical strength values are significantly higher than the minimum requirement standard.
  The high values obtained in this study are mainly due to the soil mix that incorporates a pyroclastic inert, 'azolo', which gives increased resistance to compression and is traditionally used to improve mechanical strength in the production of concrete and mortar.
- The effects of fibre addition on failure mode of samples are to improve ductility of the material by changing the failure mode of samples.

The addition of SWF in raw earth reduces the dry density, cracking, and shrinkage rate. This study intends to fill the lack of knowledge considering the mechanical effects of animal fibers on rammed earth materials. However, there is still a lack of experimental data on the effect of SWF fiber reinforcement on the fracture performance of earthen materials, with special reference to properties controlling crack initiation and propagation, and to energy absorption capabilities at large deformation regimes. A further detailed study should be able to evaluate, by means of Scanning Electron Microscope (SEM) and Energy Dispersive X-Ray (EDX) techniques, the fiber-matrix bonding for a better understanding of the mechanical performance of raw earth materials reinforced with sheep wool fibers as well as the thermal behavior, moisture absorption and desorption, and their lifetime behavior.

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Conflicts of Interest: The authors declare no conflict of interest.

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

(Full paper, published on International Journal of Sustainable Engineering in February 2022)

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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 at the same time are sustainable, with low impact, renewable and recyclable.

In this context, in the last few years, the use of natural fibres as potential reinforcements for bio-composite materials, instead of synthetic one, received worldwide growing attention.

Among natural fibres, both animal and vegetal ones, research works reported 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 carduncululus L.* (CW) cultivation was put forward and was applied in a study area located in Southern Italy, which is highly characterised by this horticultural cultivation.

Firstly, those areas with the highest concentration of *Cynara carduncululus L.* cultivation were identified, then a suitable index, which describes the agricultural wastes amount from cardoon cultivation, was developed by considering that, among the ground biomass, (i.e., 80-85% of the cardoon cultivation) the residues, namely leaves and stems, represent the 60% and 40% respectively.

Obtained results by the computation of CW amount were adopted and applied in GIS for developing tailored heatmaps that show at territorial level the distribution of the available cardoon stems fibres recyclable as potential reinforcements for bio-composite materials. As an additional natural fibre, sheep wool fibre was also considered in the study area due to the high presence of sheep. The estimated available cardoon stems yearly amount was combined with sheep wool fibre yearly amount and reported in a GIS map.

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.

Keywords: *natural fibres, Cynara cardunculus L., GIS-based model, circular economy, sustainability*

7.1 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 reduces impact on environment, by reducing CO_2 emission, air and water pollution, waste solid production, and saving energy (Asdrubali et al., 2015). Since the eco-friendly materials are generally obtained by using natural and renewable sources that are not commonly employed for construction (Maalouf et al., 2017), 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, 2020). 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 realize a new material with performant physical and mechanical behaviours (Fagone et al., 2019). 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, 2005; Liuzzi et al., 2017; Fagone et al., 2019; Galán-Marín et al., 2011; 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 (Vitrone et al., 2021). The most widely natural 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 natural fibres, such like okra (De Rosa et al., 2010) and isora (Mathew et al., 2006), as reinforcement for bio-composite materials. 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). Natural 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 differs 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 vegetables fibres. Among natural fibres, thanks to its mechanical characteristics, *Cynara cardunculus L.* fibres *(CW)* is 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 no-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 of, in order to investigate the possibility of using globe artichoke natural fibres as reinforced composites, Fiore et al., (2011) carried out an experimental trial for the identification of microstructure, chemical composition and mechanical properties of cardoon stem fibres, with the aim of evaluate 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 (Fagone et al., 2019). By obtained results, comparable to those of other natural fibres (Elanchezhian et al., 2018), it has been demonstrated that artichoke fibres, coming from the recovering of cardoon stems, are suitable to replace synthetic fibres as reinforcement in composite structures. Nowadays, data on the exact amount of these fibres is 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 natural fibres by its recycling process and to support new eco building materials production. In detail, this research study focused on the first step of post-cultivation management of *Cynara carduncululus 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 carduncululus, and Sicily is the region with the yearly higher carduncululus production, followed by Apulia (Istat, 2021). A large amount of waste, about 80–85% of this cultivation ground biomass was produced (Pandino et al., 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 is 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, organizing, analysing, and visualizing geographical data related to CW (Zubaryeva et al., 2012; Höhn et al., 2014; Valenti et al., 2018; Selim et al., 2018; Abbasi et al., 2020; Zolfaghary et al., 2021; Parlato et al., 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 stems 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 localization and the availability of these two different natural 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 natural 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.

7.2 Materials and methods

7.2.1 2.1. Cynara carduncululus L.

Cynara carduncululus 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 trough 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 et al., 2011):

Table 1 - Chemical composition of cardoons fibres

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

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

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	37.5-55
Flax	1.38	700-1,000	60-70
Hemp	1.35	530-1,110	45
Ramie	1.44	915	23
Banana	1.35	721.5-910	29
Bagasse	1.2	290	17
Henequen	1.4	500	13.2
Pineapple	1.5	1,020-1,600	71
Kenaf	1.2	745-930	41
Coir	1.2	140.5-175	6
Sisal	1.2	460-855	15.5
Abaca	1.5	410-810	41
Cotton	1.21	250-500	6-10
Nettle	1.51	650	38
Cardoons*	1.58	200	11.62

* (Fiore et al., 2011)

For this reason, cardoon fibres are suitable to be used as reinforcement fibres for bio-composites.

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

7.2.2 Study Area

Sicily is a Southern region of Italy divided into 9 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).

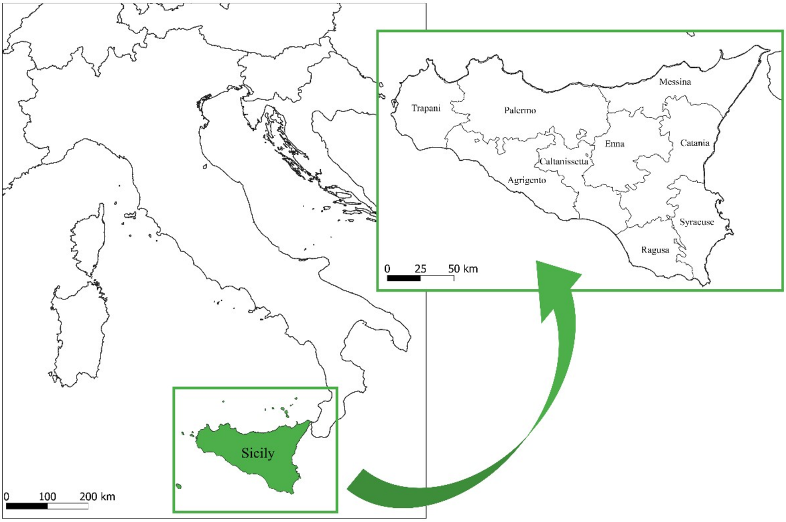

Figure 1 - Study area geographic position.

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 Utilized Agricultural Area (UAA), equal to over 1.387 million hectares which correspond to about 10.8% of the national UAA (Badami et al., 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 Table 3 and Table 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.

Table 3 - Italian cultivated area for horticultural crops and *Carduncululus* cultivation (ha).

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

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

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 Carduncubus 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 same time-interval (2016-2020) and focusing on the carduncubus production.

By considering the production, as it shown in Table 4, again Veneto, 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 2.9 million t/y, 2.4 million t/y and little less than 1 million t/y.

Instead of, by focusing on the carduncubus 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 a slight increase (+1.2%) by rising from about 950,000 t/y to more than 1 million t/y, while the production of carduncubus was kept almost unchanged (Table 4).

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

Table 4 - Italian production of horticultural crops and *Carduncululus* cultivation (t).

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

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

Since, as reported in both Table 3 and Table 4, Sicily is the region with the highest cultivated area and above all the highest production of *Cynara carduncululus L.*, it was selected as study area.

7.3 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 Carduncululus 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 Carduncululus cultivation and with the highest amount of its production were identified and localized 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 localizing 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 for acquiring data relating to the horticultural cultivations by selected a five-year time interval (2016 – 2020).

In detail, data concerning *carduncululus* 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 for providing distribution of both cultivation surface areas and carduncululus 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 maximizing 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 ($cardoon\ stem$) for describing the amount of cardoons stems availability by applying the following equation:

$$Cardoon\ stem = 40\%\ CW \qquad (1)$$

where:

CW represents the total amount of wastes, which correspond to about the 80-85% of the artichoke ground biomass (Pandino et al. 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 natural 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 centroids 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 natural 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.

7.4 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 Carduncculus cultivation and production. Data were organised for showing 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 carduncculus 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 carduncculus 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 Carduncculus 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 carduncculus cultivated surface area in Sicily.

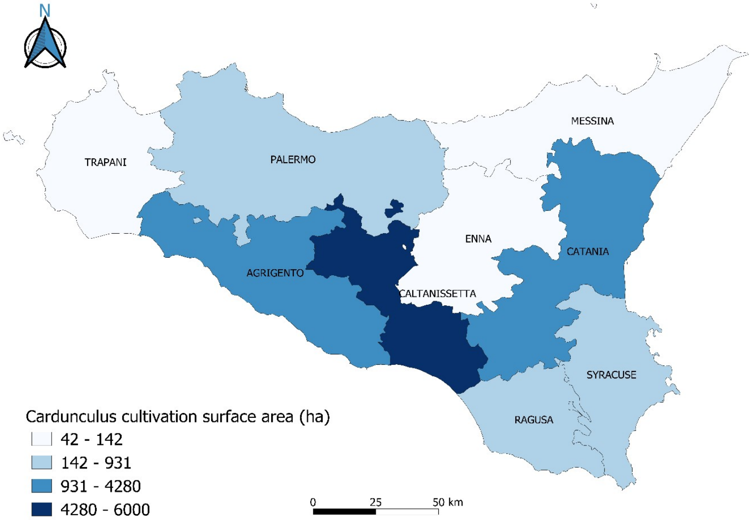

Figure 2 - Distribution of *carduncculus* cultivated surface area within the Sicily region

Since the areas with the highest surface of cultivated area do not always correspond to those with the highest production, the carduncelus 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.

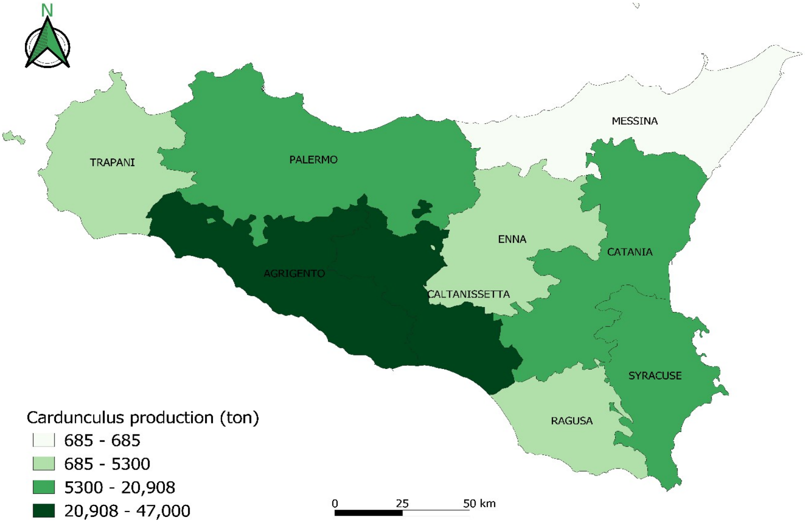

Figure 3 - Carduncelus production distribution within Sicily region

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

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

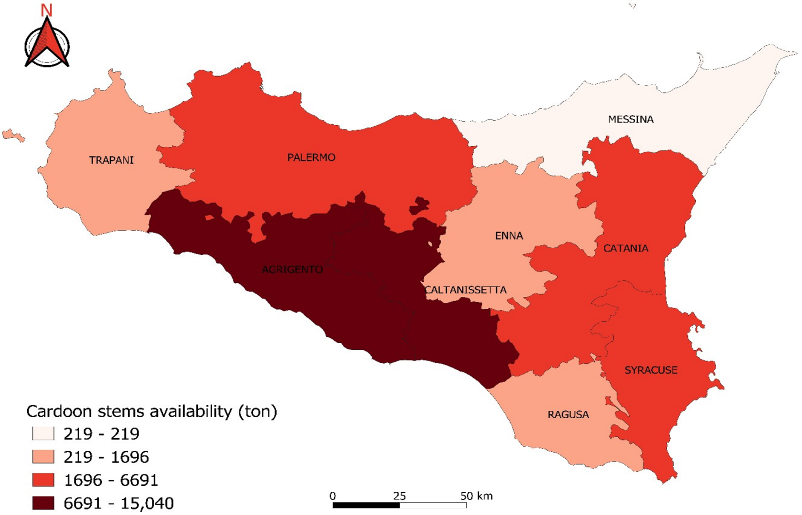

Figure 4 - Available cardoon stems distribution within Sicily region

Data showed in Figure 4 confirmed the provinces of Caltanissetta and Agrigento as those ones with the highest availability of potential recyclable natural 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).

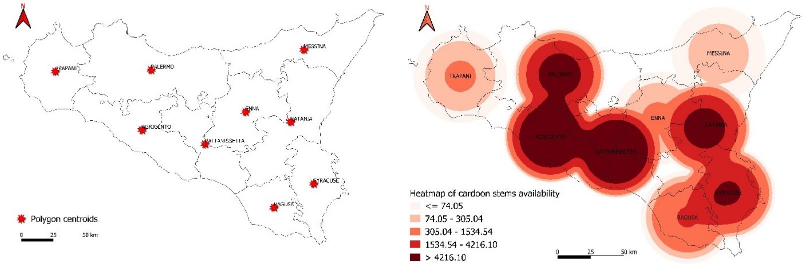

Figure 5 - Cardoon stems distribution. (a). Polygon centroid for developing heatmaps. (b). Heatmap distribution based on the computed cardoon stem production

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 regards the province 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 Figure5b concerning the amount and location of cardoon stems 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 optimize the collection process and therefore reduce CO_2 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 et al., 2011).

Since, as reported by several authors in literature, (Picuno et al., 2013; 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 natural fibres, i.e., fibre extracted by cardoon stems and sheep wool fibre (Galan-Marin et al., 2016), as reinforcements for biocomposite 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 matrixes, such as unfired clay adobe or cement mortar (Galan-Marin et al., 2010; Mounir et al.,2015).

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 on 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.

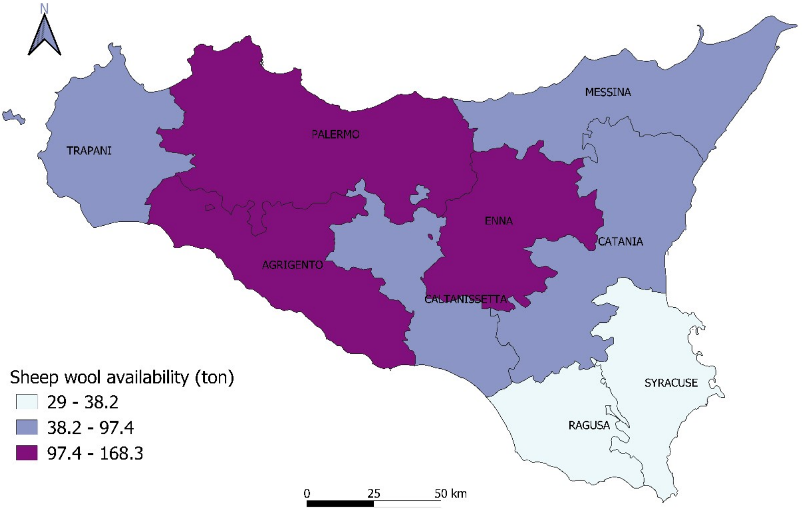

Figure 6 - Distribution within Sicily region of the recyclable sheep wool natural fibres as potentially reinforcements for bio-composite material

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, a map was produced in order to define the most representative area by combining these two natural fibres (Figure 7).

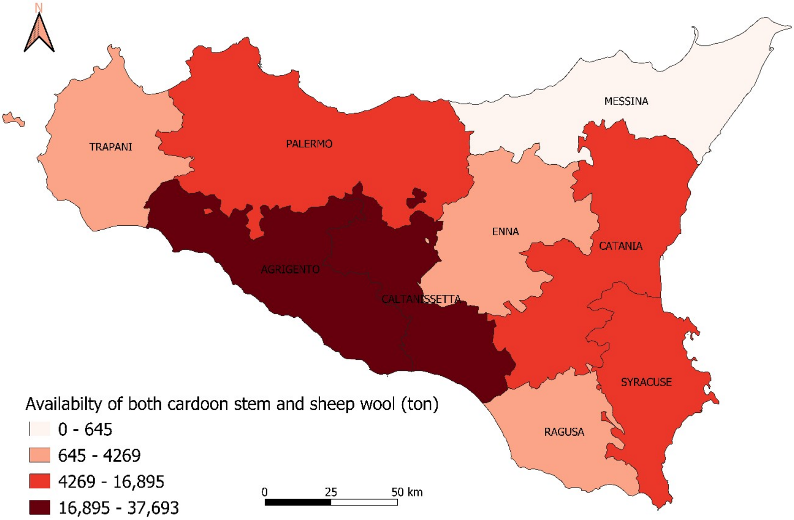

Figure 7 - Distribution within Sicily region of both recyclable sheep wool and cardoon stem natural fibres as potentially reinforcements for bio-composite material

From Figure 7 the provinces of Caltanissetta and Agrigento resulted as the most proper for locating collection centres due to the highly 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 et al., 2014; Osmani and Zhang, 2017), the optimization 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).

7.5 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 *Carduncculus* cultivation, was deeply investigated by elaborating the data related both the cultivation surface area and its production for producing GIS maps. The achieved results by the developed GIS-based model contributes to fill the gap in the knowledge of the production and localisation of cardoon stems as potential reinforcement natural fibres by its recycling process and to support new eco building materials 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.

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 fibres localization was considered for the same purpose abovementioned, 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.

Author contributions:

Parlato Monica C.M.: Conceptualization, Methodology, Writing-Original draft preparation, Writing- Reviewing and Editing. Valenti Francesca: Methodology, Formal analysis, Data curation, Software, Writing- Reviewing and Editing, Supervision. Lanza Elisa: Writing-Original draft preparation. Porto Simona M.C.: Visualization

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8 Conclusions

Sustainability and energy efficiency in building sector are based on decrease primary energy demand, on lower CO_2 emissions, and on to improve ecological behaviors of building materials, traditional or not. In particular, the use of alternative materials obtained by recycling wastes, i.e., agricultural wastes, is challenging to increase sustainability of buildings.

Moreover, the valorization of the locally available materials, such as agricultural wastes, co-products or by-products, and their use on rural buildings plays a crucial role for a sustainable development, especially in the rural areas.

The worldwide increasing of agricultural production causes a huge amount of agricultural wastes (AW) (about 998 million tons yearly/production) that represents a serious issue for air, water, and plants pollution, and generally for landscape quality, mainly in rural area.

This PhD study addressed the potential valorization of some agricultural wastes and their conversion in new resources for building sector.

In accordance with Circular Economy statement and Green Deal Agenda, it has been evaluated the potential re use of AW (i.e., plastic films for covering protected crop, sheep wool, and cardoon stem), and their valorization to obtain new eco building components (e.g., renewable, healthy for both production process and application, locally available, with a low manufacture and environmental impact).

A potential re-use of AW is based on their properly disposal management of. Five phases constituted a correct disposal strategy policy: collection, storage, treatment, transfer, and utilization. The whole re-use process starting with an accurate evaluation of the production and localization of wastes.

For this reason, in the first part of this research, a GIS-based model was developed with the aim of filling the gap in the knowledge of the production and localization of the yearly amount of the considered wastes.

The obtained results could be useful for planning tailored collected centers as near as possible to those areas where these wastes are highly produced.

This aspect is relevant for a sustainable valorization by paying attention to the transport costs during the logistics and supply phase (i.e., from the cultivated fields to the collection centers), with an advantage in terms of environmental and social impacts, and costs. After this phase a deeply experimental trial has been carried out.

Firstly, a physical and mechanical characterization of "*Valle del Belice*" wool fibres was carried out with the aim of a possible alternative use of this agricultural special waste as strengthening system for rammed earth building components.

Tensile tests results were comparable to those reported in literature with an average strength of 137.31 MPa and an initial secant modulus of 1,739.41 MPa have been found, that confirm the suitability of these fibres as a reinforcement material for raw earth mixtures.

Following, it was evaluated mechanical behaviours of raw earth specimens reinforced by this kind of sheep wool fibres.

Mechanical properties of different soil mix added with a livestock waste, sheep wool fibres, have been evaluated and compared. As stated in literature, the introduction of reinforcement fibres on raw earth material improves shrinkage rate, post-fracture performance, reduce dry density, and in case of longer fibres increase of the composite material.

Test results appear to encourage the possibility of the use of greasy wool in the building sector, fulfilling the proposed aim of the research. This practice could decrease environmental pollution by reducing a huge amount of livestock wastes related to low-quality wool from dairy sheep also bringing benefits to the breeders. The improvement of the mechanical behaviours of raw earth-based materials by using natural fibres coming from a special agricultural waste, instead of synthetic ones, it is relevant to improve the environmental sustainability of the building sector.

In the future, should be investigated the behaviors of cardoons stem and the combination with sheep wool fibres for new kind of composites by analyzing mechanical properties as already done for sheep wool.

As stated by obtained results, 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.

Furthermore, a Life Cycle Assessment, of the whole process of these new industrial chains, it is necessary to evaluate their realization. Some aspects concerning the whole manufacturing process to convert agricultural wastes into building materials, such as the correct scale required for a sustainable production of them, should be further investigated.

9 Supplementary materials

9.1 OHTERS ACTIVITIES

In this paragraph are reported the accepted abstracts produced during my PhD course for the attendance as presenting authors to international conference.

9.1.1 International Mid-Term Conference 2019 Italian Association of Agricultural Engineering (AIIA). Potenza – Matera, University of Basilicata, September 12-13, 2019

9.1.1.1 Title: Heatmap Production for Greenhouse Plastics Waste Management

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Keywords: plastics waste management; land management; sustainability; GIS modelling; spatial index.

Abstract

Yearly in Europe, more than 1 million tonnes of Agricultural Plastic Waste (APW) are generated, and in particular, in Italy, more than about 350,000 tonnes of agricultural plastic materials are used. Nowadays, the use of plastic materials is considered in protected cultivation for a number of components such as crop shelter coverings, irrigation pipes, mulching films, packaging, and seedling containers. Application of plastic films for coverings in protected cultivation enables a significant advantage for the production system by obtaining a shortening of the growing season. However, in the absence of a correct disposal management of plastic waste, environmental degradation could take place with serious ecological and economic consequences.

In this study, land use analysis related to protected crops was carried out in a study area with the final aim of quantifying the yearly amount of APW coming from crop shelter coverage. The study area was localised in the province of Ragusa, the area with the highest concentration of protected crops in Italy constituting approximately 57% of the total national surface.

Firstly, the areas with the highest density of crop shelters (i.e., greenhouses and tunnels) were mapped by implementing a GIS (Geographical Information System) populated with data collected from land use maps, digital colour orthophotos, and remote sensing images. The results of this first phase showed that the density of greenhouses and tunnels is still elevated nearby the coastline, highlighting that the indications of the territorial plan of the Province of Ragusa concerning the movement of protected crops from the coast to the internal rural areas were disregarded. Within the high-density areas, thirty samples, each one of about 150 ha, were selected and analysed in order to classify crop shelter into typologies.

Next, a suitable index for computing APW was chosen from literature and was computed to obtain the related heatmaps. Finally, sensitivity analyses were carried out by varying thickness, lifetime, and density of the covering films of the greenhouses and tunnels located in the considered samples. The index ranged between 2,484 kg $ha^{-1}year^{-1}$ and 976 kg $ha^{-1}year^{-1}$.

Results of the study provide basic information for analysing the environmental impact due to transportation of APW to collection centres, recycling industries or landfills located in the neighbouring of the study area.

9.1.2 RETASTE: Rethink Food Waste Conference” Hellenic Mediterranean University Harokopio University, Athens 6-8 May 2021.

9.1.2.1 *Title: Raw Earth-based Building Materials: an Exploration of Mechanical Behaviour of Floridia Soil-based Adobes*

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Abstract

Raw earth, with wood and stone, has a place among the oldest building materials used in the world. Nowadays, on a circular economic context, researchers’ interest in raw earthbased building materials has been growing because they are highly available and environmentally friendly. The use of this traditional material has positive environmental consequences, especially in traditional rural building reuse and in rural landscape preservation. In fact, raw earth is locally available and totally recyclable and, thanks to its perfect integration into the landscape, it improves site visual perception. Often, in order to increase mechanical performances and durability of earth materials additives and/or chemical stabilizer agents (i.e., Portland cement) are used to produce raw earthbased building components. This production process reduces the environmental sustainability of the base material and causes a relevant increase on the embodied energy. This research work aimed at investigating how to improve the mix-design of earth-based building materials in order to increase their mechanical properties without addition of chemical agents. A physical stabilization was performed on an original texture soil, through the addition of different particle sizes. Mechanical tests have been carried out on five different soil mixes by changing soil composition, aggregates, and water. Specimens realized with the mix-design 5 showed best results of flexural and compressive strength values with 1.65 MPa and 6.74 MPa, respectively. Mix 3 obtained the lower linear shrinkage rate (6.04%). Since raw earth-based materials are highly sensitive to soil composition and aggregates, the attempt of this study is to obtain a repeatable process to produce semi-industrial adobes by the optimization and control of different natural materials (i.e., soils, aggregates, and water).

Keywords: *raw earth building components, physical stabilization, mechanical tests, circular economy, sustainability.*

9.1.3 Biocatalysis & Green Chemistry Conference, Coalesce Research Group, 33 Market Point Dr, Greenville, SC 29607, USA, Virtual event June 24-25, 2021

9.1.3.1 Title: GREENHOUSE COVERING PLASTICS FILMS WASTE MANAGEMENT: A Case-Study GIS - BASED MODEL

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Abstract

Background: In a circular economy framework, the conversion of waste into new raw material is an important aspect of increasing resource efficiency, by reducing environmental pollution and CO_2 emission. One of the biggest environmental concerns is plastic pollution, a cause of the long-life material (plastic can take hundreds or thousands of years to be decomposed) and because more than 85% of plastic waste ends up in landfills or are wrongly disposed of.

In Europe, plastic material, especially plastic films, used in agricultural activities are more than 1 million tons per year. In the absence of a correct policy disposal of plastic films, environmental degradation take place with serious consequences for air, water and landfill.

Objective: In this research, a geographical information system (GIS) - based model to locate and quantify the yearly amount of agricultural plastic waste (APW) coming from crop-shelter coverage used in greenhouses system was put forward and was applied in a study area located in southern Italy, the Province of Ragusa, highly characterized by protected cultivation practices.

Methods: The areas with the highest density of crop shelters were mapped, then a suitable index to determine APW amount was computed and applied to obtain heat maps related to covering plastic films.

Results: The computed average values of PWI_G and PWI_T were 1,477 kg $ha^{-1}yr^{-1}$ and 1,978 kg $ha^{-1}yr^{-1}$, respectively.

Conclusion: GIS-based model results could provide basic information for the analysis of the environmental impact due to transportation of APW. Therefore, these results could offer a suitable tool to improve the correct disposal management of covering plastic films and the related recycle policy.

9.1.4 RAGUSA SHWA 2021 Conference, Scicli, 15 -16 September 2021

9.1.4.1 Title: Spatial Analyses to Assess the availability of Sheep Wool as Potential Building Component

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Abstract

Objectives

In the Mediterranean area, rural buildings are usually built without a specific temperature control system. The use of natural insulation systems, i.e., sheep wool-based materials, could improve their thermal efficiency by optimizing the building passive conditioning systems. The employ of sheep wool as thermal insulating material represents a consistent advantage for some types of rural buildings where the control of microclimatic conditions is of relevant importance regarding their main functional destination (i.e., buildings for intensive animal breeding, buildings for agroindustry). Sheep wool is suitable as thermal and acoustical insulation material thanks to its capacity to absorb the exceeding moisture and to isolate from vibrations. Moreover, sheep wool neutralizes harmful and odorous substances such as Nitrogen Dioxide, Sulphur Dioxide, Toluene, and Formaldehydes. By using sheep wool insulation indoor air quality (IAQ) and human and/or animal wellness improve.

The main objective of this work was to investigate the yearly availability of sheep wool, as an alternative to common insulation materials (e.g., fiberglass, rock wool, polyurethane foam, polystyrene).

Currently, sheep wool is an agricultural special waste contaminated with impurities, with high disposal costs for breeder and often illegally disposed (e.g., buried or burned), with a strong environmental impact.

Methods

In this study, a GIS - based model to locate and quantify the yearly amount of livestock co-production, i.e., sheep wool, coming from dairy sheep breeding, was put forward and was applied in a study area located in Southern Italy, highly characterised by this kind of breeding.

Results

The GIS-based model provided the localization and the yearly amount of sheep wool to evaluate its availability as new eco-friendly material. Moreover, these are basic information for the analysis of the environmental impact related to the logistics and transportation phase of sheep wool to the collection centers.

Keywords: *SHW in Building, natural material, sheep wool, natural insulation materials, GIS-based model*

9.1.5 *2021 IEEE INTERNATIONAL WORKSHOP ON METROLOGY FOR AGRICULTURE AND FORESTRY, Trento – Bolzano 3-5 November 2021*

9.1.5.1 Title: GIS based model to locate and quantify agricultural wastes for sustainable building components: plastic films and sheep wool fibers

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Abstract

Nowadays, the interest for environmental sustainability, energy, and efficiency constructions, generally known as Green Buildings, it is strongly increasing. Procedures adopted for Green Buildings are often based on both the reduction of environmental impact of buildings and the improvement of human and animal wellness. This study stems from the need to reuse agricultural wastes (AW) for producing sustainable materials to be used for the construction or renovation of rural buildings. Since a sustainable reuse of AW depends on their availability and geographical location, a methodology was put forward to locate and quantify the wastes considered in this research study i.e., plastic films used for protected crops and sheep wool. By using a Geographical Information System (GIS), land use analysis was carried out in an area with the highest concentration of protected crops in Italy (Ragusa province). A suitable index for computing Agricultural

Plastic Wastes (APW) was chosen from literature. Furthermore, by using data supplied by National Zootechnical Registry, a dedicated GIS was developed to localize and quantify sheep and breeder's sheep in Sicily. This first part of the research provides basic information useful for planning tailored collection centers as near as possible to those areas where these wastes are highly produced by also analyzing the environmental impact due their localization.

Keywords—agricultural wastes, ecofriendly materials, plastic films, sheep wool, GIS, spatial analysis

9.2 SEM (Scanning Electron Microscopes) – SHEEP WOOL REPORT

In this paragraph is reported the SEM (Scanning Electron Microscopes) – SHEEP WOOL Report.

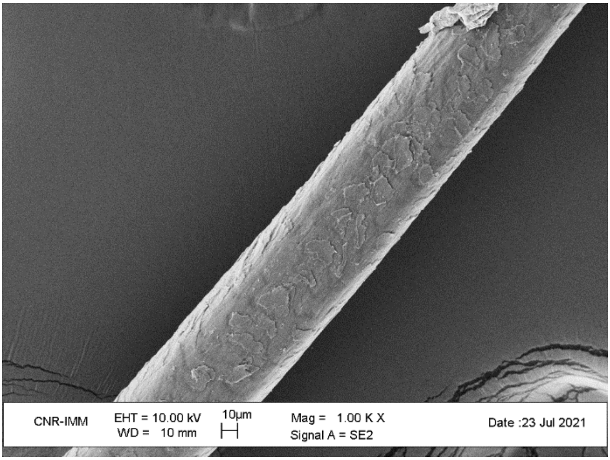
On 21/07/2021, at "*Torre Biologica*" - University of Catania which Via S. Sofia, 89, 95123 Catania CT, it was carried out the preparation of the wool sample for observation by an electronic microscope.
The procedure carried out for the preparation of the sample was as follows:
1. Inside the glass plate, a cotton pad has been placed at the center.
2. The fragments of wool, thanks to the aid of a scalpel, were positioned inside the glass plate.
3. Then all the lights inside the hood were turned off (to avoid the reduction of tetroxide) and osmium tetroxide was added with a Pasteur over the cotton pad.
4. The glass plate was closed with the lid and wrapped with aluminum in order to avoid oxidation of the osmium tetroxide by the light.
5. After 2 hours, the cotton pad inside the plate was removed and closed again, leaving the aluminum open to allow the sample to dry in the air, pending further operations carried out on 22/07 / 21.
1. On 22/07/21, after opening the plate, we noticed that osmium blackened our sample.
2. Insert in the sample holder (pin stub) about 1.2 cm a carbon disk that will allow our sample to adhere to the stub.
3. With the help of the tweezers, we take our fragment of wool from the glass plate and place it on the stub.
4. We try to attach the sample to the stub well, avoiding touching it and pressing it too much with the tweezers on the top of the sample, since it will be the one that will allow the observation to the SEM.
5. Cover the box where the sample is placed with aluminum to prevent osmium from reducing.

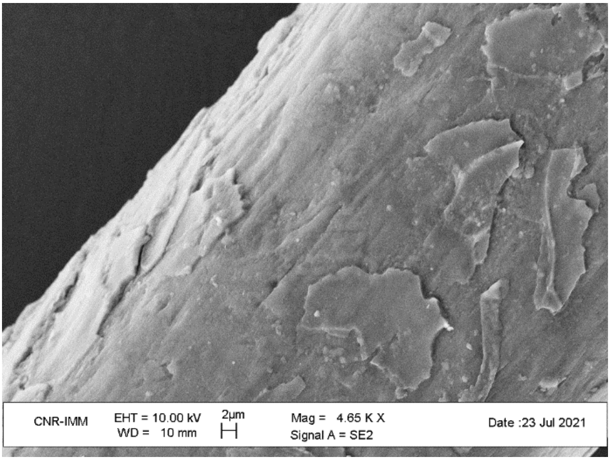
6. The next step is gold metallization using the sputter coater. This step is carried out because the scanning electron microscope can analyze some samples that are more problematic and require additional preparation to allow the operator to obtain high quality information; this preparation consists in metallizing the sample with a thin layer (~ 10 nm) of a conductive material, such as gold. The samples that are metallized before being loaded into the SEM are those that are sensitive to the electron beam. They are mainly biological samples, but they can also be of other types, such as materials deriving from plastics. The electron beam in the SEM has a very high energy and during the interaction with the sample it transfers a part of it to the sample, mainly in the form of heat. If the material is sensitive to the electron beam, the interaction can damage part of its structure. In this case, the covering with a material that is not sensitive to the beam constitutes a protective layer against this kind of damage.

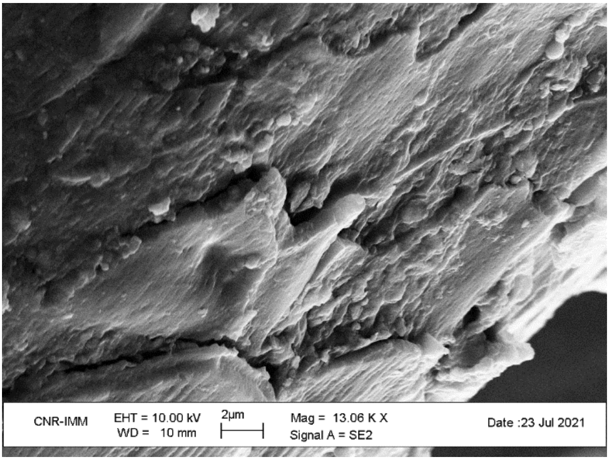
7. Then a vacuum is created inside the machine (sputter coater) up to a pressure of 0.01 mbar.

8. Then, we carry out a 5-minute cycle to cover our sample with the gold coating.

9. We insert our metallized sample inside the SEM and create the vacuum up to - 5tor.
10. Let's start the observation.






CNR-IMM
EHT = 10.00 kV
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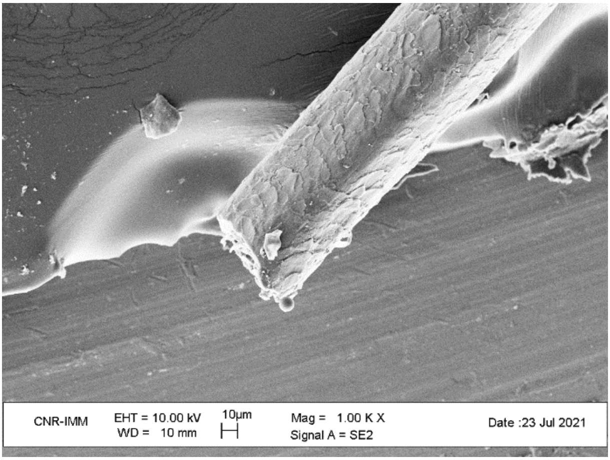
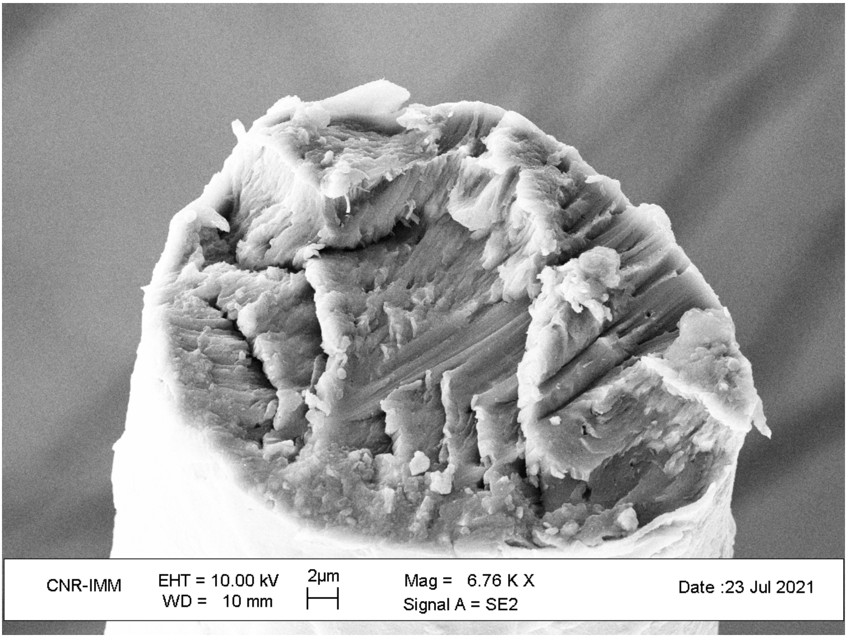
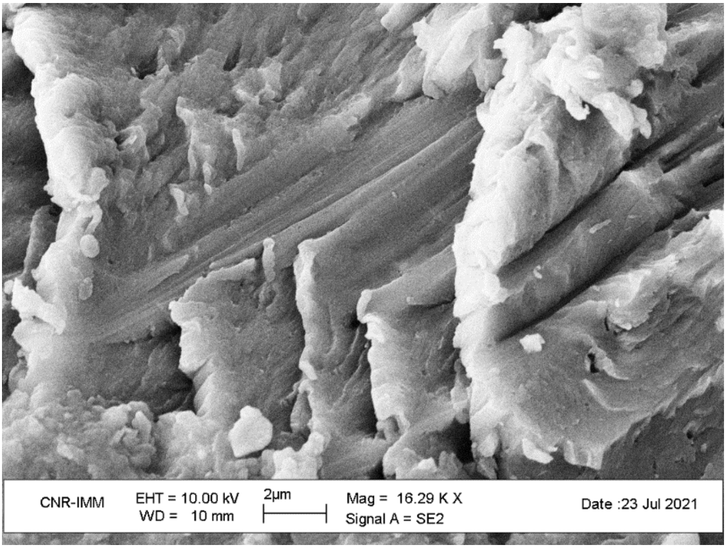
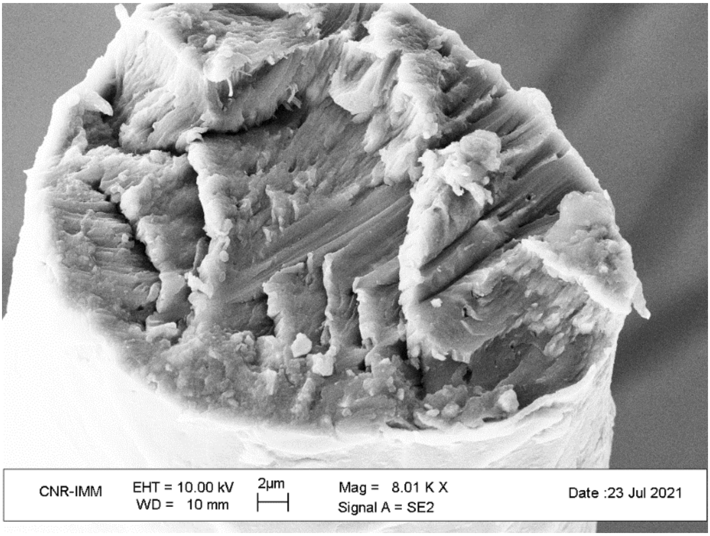
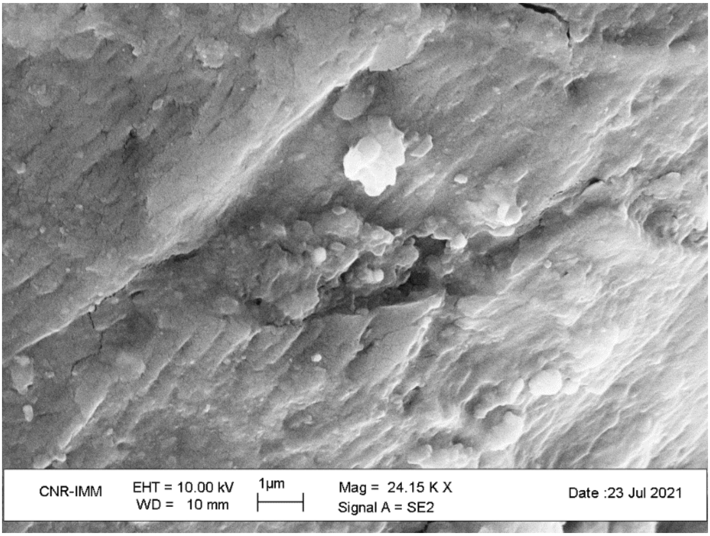
Signal A = SE2
Date :23 Jul 2021

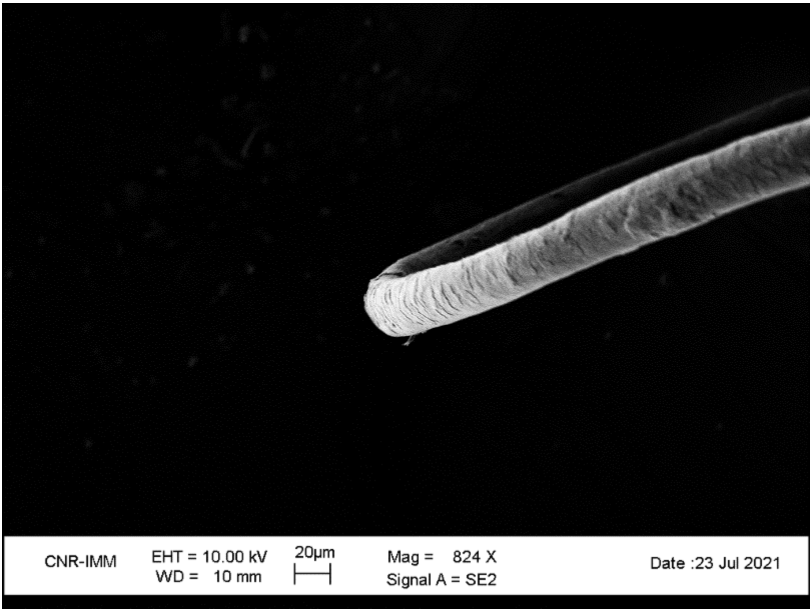

CNR-IMM
EHT = 10.00 kV
WD = 10 mm
10µm
Mag = 1.00 K X
Signal A = SE2
Date :23 Jul 2021

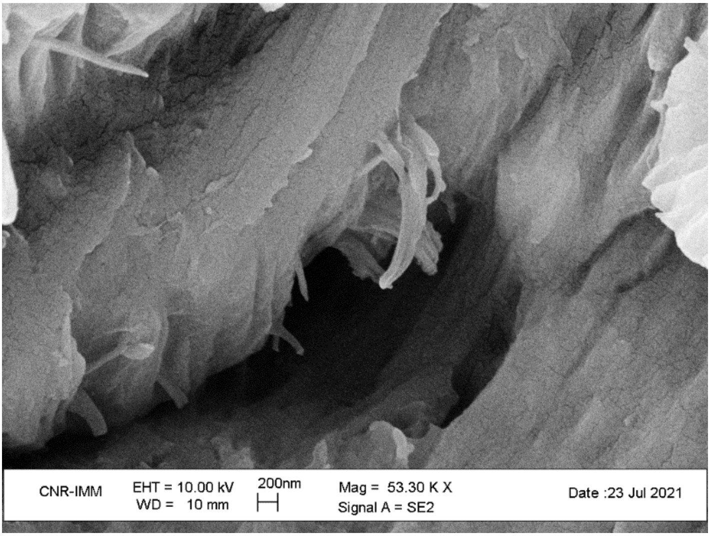

CNR-IMM
EHT = 10.00 kV
WD = 10 mm
2µm
Mag = 6.76 K X
Signal A = SE2
Date :23 Jul 2021


CNR-IMM
EHT = 10.00 kV
WD = 10 mm
2µm
Mag = 16.29 K X
Signal A = SE2
Date :23 Jul 2021


CNR-IMM
EHT = 10.00 kV
WD = 10 mm
2µm
Mag = 8.01 K X
Signal A = SE2
Date :23 Jul 2021


CNR-IMM
EHT = 10.00 kV
WD = 10 mm
1µm
Mag = 24.15 K X
Signal A = SE2
Date :23 Jul 2021


CNR-IMM
EHT = 10.00 kV
WD = 10 mm
20µm
Mag = 824 X
Signal A = SE2
Date :23 Jul 2021


CNR-IMM
EHT = 10.00 kV
WD = 10 mm
200nm
Mag = 53.30 K X
Signal A = SE2
Date :23 Jul 2021