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EVALUATION AND APPLICATION OF OPUNTIA FICUS-INDICA PANEL

A.De Vecchi[1], A. Valenza[2], S. Colajanni[1], E. Sanfilippo[1], V. Fiore[2], A. Lanza Volpe[1]

[1] Dipartimento di Architettura, Università di Palermo, Viale delle Scienze, 90128 Palermo, Italy
[2] DICAM, Università di Palermo, Viale delle Scienze, 90128 Palermo, Italy

*Corresponding author; e-mail: simona.colajanni@unipa.it

Abstract

Today the attention to the building sustainability issue is increasingly important, because of the major responsibility of the buildings field in the environmental degradation: both in terms of energy consumption from non-renewable sources and the raw materials impoverishment. In addition, the level of comfort required by users are growing and the thermal insulation of buildings becomes the key element in the reduction of energy consumption and $C0_2$ emissions, both in the case of new construction and existing ones. The thermal insulation of buildings is the key element in the reduction of energy consumption and $C0_2$ emissions due to the cooling of building interiors, both in the case of new constructions and for old ones. Nowadays the heat load of a building depends on the presence of insulation materials which determines the performance of the building envelope. The main goal of this work is both to present the production technology of a new eco-friendly panel and to evaluate its thermal insulation performances, also comparing to those of the most diffused insulation materials available in the market. Particularly a new panel was produced by using the cladodes of Opuntia ficus-indica, a widespread plant in Sicily, according to the principles of sustainable and eco-friendly development. In particular, the cladodes of this plant were properly dried, shredded, sorted and mixed with a polyester resin as binder, to make a rigid panel. To evaluate the influence of the resin on the insulation properties, it was also manufactured a reference panel, with only Opuntia ficus-indica granules. The prototypes realized have shown thermal performance that can be considered satisfying and competitive with those of other commercially available panels. During this phase, therefore, it has been compared the potential of the proposed insulating panel with those of the commercial panels, through the evaluation of the thermal and dynamics characteristics of four different possible stratigraphic configuration of vertical external walls.

Keywords:

Thermal insulation; Building envelope; Energy saving; Insulating panel, Natural material; Opuntia ficus-indica

1 INTRODUCTION

The main goal of this work is to present the production technology of a new eco-friendly panel, by demonstrating its thermal insulation characteristic, comparing to the most diffused insulation materials available in the market. This panel was produced starting, as raw material, from the fresh stems, commonly named cladodes, of Opuntia ficus-indica, which appropriately cleaned, dried, grinded and sifted were mixed with a polyester resin as binder. The prickly pear or Opuntia ficus-indica is a plant, member of the Cactaceae family, originated from the American continent and reached the Mediterranean countries during the 16th century. It is mainly cultivated for fruit production but young shoots are also eaten as vegetables in Mexico and southern USA. In the industrialized countries of the Mediterranean area, cladodes are not an usual nutritional source for humans, but the fruits are largely consumed.

Sicily ranks second among all countries in the world for producing and exporting prickly pear fruits (Figure 1). In North Africa, the cultivation of this plant is used both against the soil erosion in arid areas, and as forage replacement during droughts [Vignon 2004]. In the literature there are several research works which encourage nutritional studies to assess the importance of prickly pear in the maintenance of health and disease prevention, thanks to their antioxidant and antiulcerogenic properties [Butera 2002], [Galati 2003]. Opuntia ficus-indica is commonly used also in traditional medicine both for its hypoglycemic actions [Hegwood 1990] and for its healing activity as cicatrizant [Galati 2003]. Moreover some researchers have used this plant to obtain fibers as reinforcement of composite materials.

Fig. 1: Cultivation of Opuntia ficus-indica

Particularly, some researchers [Malainine 2004] obtained a lignocellulosic flour by grinding dried cladodes of Opuntia ficus-indica and used it as low cost natural filler in polypropylene-based composites.

Moreover, nanocomposite materials have been manufactured by casting and evaporating a mixture of aqueous suspensions containing cellulose microfibrils and an aqueous suspension of a copolymer of styrene and butyl acrylate, as matrix [7]. Other uses have been reported for Opuntia ficus-indica, including as a binding and impermeabilization agent in the restoration of historical buildings [Cardenas 1998].

The cladodes of this plant, flattened and oval in shape, 30 cm to 40 cm long, 15 cm to 25 cm wide and 1.5 cm to 3.0 cm thick, form branches (Figure 2). They are covered by a waxy cuticle that limits transpiration and also armed with two kinds of spines: a large, smooth and fixed one, and another kind, smaller, called glochids, that easily both detach from the plant and penetrate skin. Cladodes, around the fourth year of growth, undergo a lignification process thus making a solidtrunk [Anderson 2001].

Regarding chemical composition of the cladodes, there is a large amount of minerals (19.6 wt%) as well as waxes and fats (7.2 wt%). The lignin content is low (3.6 wt%) and the main constituents are polysaccharides (69.6 wt%), including cellulose (21.6 wt%).

On the other hand, cellulose is the main constituent (47.9 wt%) of the spines, with lignin, ashes, fat and waxes in very small amounts [Malainine 2003].

The cladodes have high water content, 95% in mass, and dehydration is prevented by its cuticle [Garcia Saucedo 2005]. They are also rich in dietary fiber, carbohydrates, minerals, proteins, and vitamins.

Furthermore, it has been documented that they have medicinal properties related to the control of high levels of blood glucose, cholesterol and pressure, and other pathologies.

Unfortunately the cladodes have a very short storage life (i.e. from 5 days at room temperature to 10 days in refrigerated environments [Rodriguez-Felix 1992]) and their dehydration offers a convenient alternative to the storage and handling of the product [López 2009]. Like other countries of the Mediterranean area, in Italy the cultivation of the plant is fairly widespread, particularly in the regions of the southern country (i.e. Sicily, Calabria, Puglia and Sardinia). According to the latest grant, the cultivation area of Sicily is today equal to 2.500 hectares, i.e. the 90% of the cultivation area of Italian Opuntia ficus-indica (Figure 1).

In spring or late summer of every year pruning is done both to prevent contact between cladodes and to eliminate those sick or damaged.Yearly a great amount of waste material, due to pruning of Opuntia ficus-indica is not re-used, resulting in disposal problems. The aim of this work is to re-use this waste material to realize an eco-friendly panel, which could be useful as thermal insulator in building field.

Nowadays the commercial products used to thermal insulate the building envelope, can be divided into three categories, according to their consistency:

- Rigid or stiff panels: it can be combined with other layers of different materials (i.e. wood, drywall or laminate) in order to increase the resistance of the structure;
- Soft panels (for instance rolls or mats): mainly used in wall cavities with only isolation function;
- Bulk materials (for instance short fibres, flakes or granules): used to fill the wall and roof cavities.

According to their nature and origin, these materials can be also classified as:

- Synthetic (e.g. organic polystyrene foams, polyurethane foams or PVC foam);
- Mineral (e.g. expanded clay, expanded perlite, vermiculite, pumice, cellular glass);
- Vegetal (cellulose or wood fibres, and lignocellulosic fibres like hemp, flax, coir, jute and cork ones);
- Protein (from animal): these materials are grouped under the categories of hair (wool), fur (angora) and secretions (silk).

The eco-friendly panel, object of this work, could represent an useful product in most applications of building field (i.e. roofs, floors, interior and exterior walls), to improve the thermal insulation of the structures. It has been manufactered witha production technology similar to those commonly used for panels commercially available and thus could be industrially produced at competitive costs.

Moreover, it is possible to obtain, as by-products, some powder and a liquid, which could be used in food, in pharmaceutical or cosmetics field. The proposed panel could also allow a substantial energy savings since the raw material is natural, waste and renewable.

2 CHARACTERIZATION OF THE PANEL

As raw materials, the cladodes, resulting from the pruning phase and aged from one to ten years, were selected, washed, deprived of the spines and cut. Regarding the cut phase, each cladode was divided in two part along the thickness in order to facilitate the water extraction.

2.1 Drying stage

Initially the cladodes were pressed with a screw-press machine to squeeze out a liquid which could be re-used for other applications (e.g. in pharmaceutical or cosmetics fields). In the case of cladodes older than four years this phase was not necessary, due to high amount of ligneous material.

The samples were then dried in a multi-mode domestic ventilated microwave oven (Figure 3) operated at 400 W and 100 °C, for a time interval between 2 h and 6 h, depending on the age of the cladodes (Table 1) to obtain useful parameters for assessment of the production process. The weight and moisture levels of each sample were measured periodically.

Fig. 2: Cladodes of Opuntia ficus-indica

Fig 3: Samples in a microwave oven

Fig.4: Dried cladodes crushed

Fig. 5: Granules sorted by size

Tab. 1 - Effect of drying treatment on samples weight

Sample	Initial weight	Drying condition		Final dry weight	Liquid	Granules	Powder
[age]	[g]	T [°C]	t [min]	[g]	[g]	[g]	[g]
2-4	2439	100	210	98	883	53	39
4-6	2298	100	290	164	-	75	87
6-10	2439	100	360	392	-	125	194

2.2 Shredding and selective grinding stages

Samples dried are first shredded through a cutting mill and then sorted by using sieves of different aperture size. The material as obtained, shown in (Figure 5), can be used both as bulk material and mixed with a binder to achieve a rigid panel. Particularly, the granules have shown an apparent density equal to about 279 Kg/m^3.

2.3 Mixing with resin

To realize a rigid panel, the granules obtained from previous phases have been mixed with a polyester resin as bonding agent. Since the primary aim of this preliminary work is to assess the insulation properties of the new ecofriendly panel, either different types of adhesive or binder nor more sophisticated equipment such as presses, autoclaves, ovens have been used.
Particularly was realized a panel with dimensions 220 x 220 x 28 mm (Figure 6) and total weight of 584 g. The apparent density of the panel was equal to 450 Kg/m^3.

Fig 6: Opuntia ficus-indica panel

Fig 7: Thermal insulation test

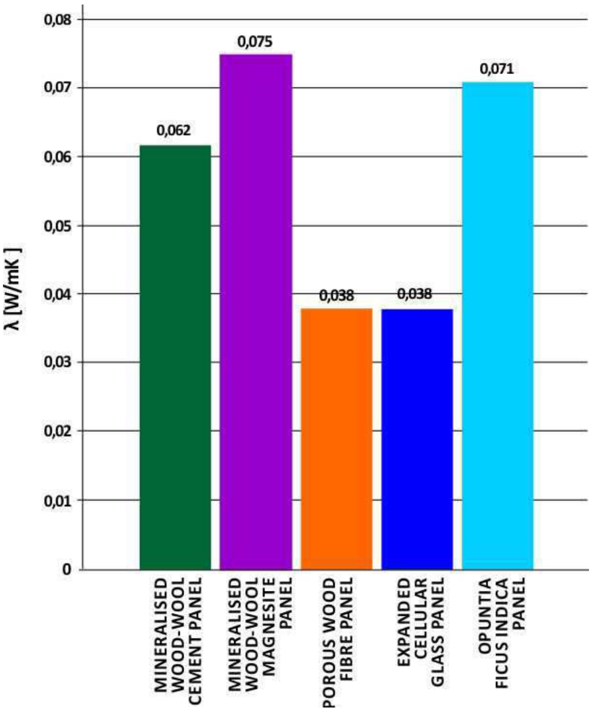


Fig. 8: Thermal conductivity of commercial rigid panel

The thickness value (i.e. 28 mm) is similar to that of other commercially available panels used while the other dimensions were chosen according to sizes of the testing machine for measuring the thermal conductivity [De Vecchi 2010]. It is important to specify that, at this early stage of research work, the panel has been realized with a resin excess.

For this reason, the weight fraction of resin will be reduced in a future phase of industrialization of the panel, by improving thus the insulation properties of the product.

3 THERMAL PROPERTIES ASSESSMENT

The thermal conductivity of the samples was measured according to ISO standards [AAVV 1991] by using a heat flow meter mod. Fox 314 by Laser Comp shown in Figure 7, at 10 °C. The samples were placed horizontally while the heat flow was vertical. The Opuntia ficus-indica panel has shown an average value of thermal conductivity equal to 0.071 W/mK. This result has been compared with the conductivity data of rigid panel actually used in several fields as thermal insulators.

As shown in Figure 8, the thermal conductibility of the new eco-friendly panel, is comparable to that of the fibre mineralized wood panel, whose performances result significantly improved thanks both to use optimized industrial techniques and most suitable binders.

On the other hand, our innovative panel shows lower insulation properties than the other commercially panels considered.

In spite of that, Opuntia ficus-indica panel can be considered less expensive in terms of energy consumption (during the production phase) compared to these commercial panels.

For instance, the porous wood fibre panel shows lower conductivity (0.038 W/mK) but his technology production is more expensive (energy consumption = 17.00 MJ/kg)[16].

To evaluate the influence of the resin on the insulation properties, it was also measured the thermal conductivity of a reference panel, realized with only Opuntia ficus-indica granules without resin as binder, with thickness equal to 21 mm.

As expected, the presence of resin lead to decrease the insulating properties: the reference panel (without resin) has shown an average thermal conductivity equal to 0.057 W/mK.

Regarding the bulk materials commonly used as insulators, the thermal conductivity of the Opuntia ficus-indica granules is comparable to that of vermiculite, lower than those of expanded clay, pumice, granulated foam glass and cellulose granules (Figure 9) [Fassi 2010].

Moreover, the reference panel is less insulating but also less expensive (as discussed above, it is a waste materials, renewable and widespread in several country of the Mediterranean area) than materials such as expanded perlite, cellulose fiber flaked and cork.

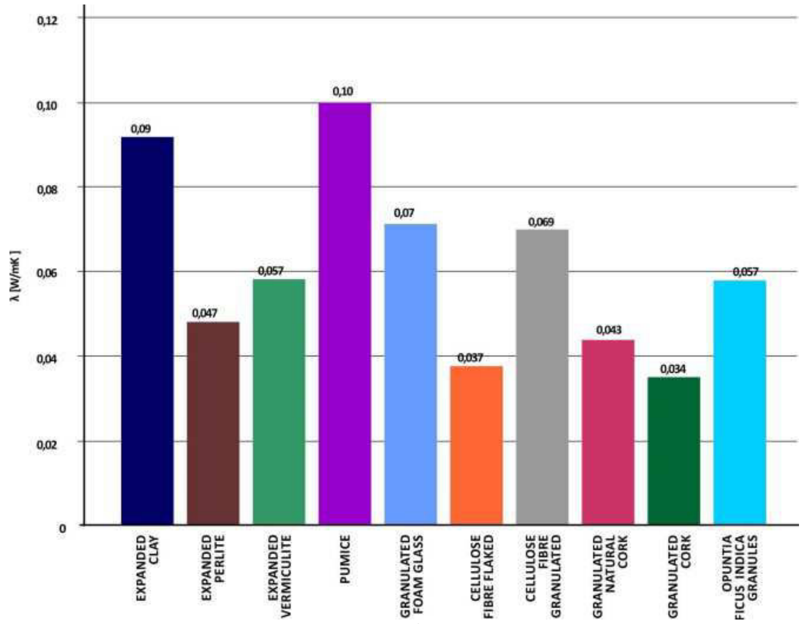


Fig.9: Thermal conductivity of commercial bulk materials.

4 COMPARISON BETWEEN THE INSULATION MATERIALS AVAILABLE ON THE MARKET

To assess the Opuntia ficus-indica panel commercial competitively on the market, we proceeded to the simulation of the answer of a typology of opaque external wall. It was taken as a reference the opaque wall (total thickness of 29 cm) of a building located in the city of Palermo that has this climatic characteristic:
- Climatic Zone: B
- 751 Degrees Day

It was considered a common stratigraphy consisting of the following layers:
- External plaster, 30 mm;
- Perforated bricks (Poroton), 250 mm;
- Plasterboard, 10 mm.

Through the application of the calculation methodology required by law UNI EN ISO 13786, the results obtained by the addition, each time, of different 80 mm insulating layers, have been evaluated, In particular (figure 10 a-b-c-d-e), it was considered the addition of of:

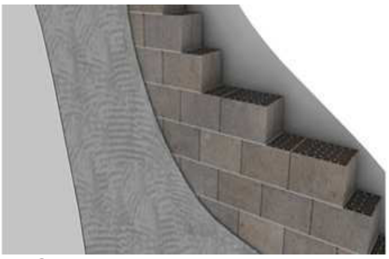
1. air cavity ($\lambda = 0.28$ W/m^{2}K);
2. polyurethane foam panel ($\lambda = 0.03$ W/m^{2}K);
3. wood fiber panel ($\lambda = 0.041$ W / m^{2}K);
4. Opuntia ficus-indica panel ($\lambda = 0.071$ W/m^{2}K).

The technical solutions proposed allows to simulate the most commonly conditions used in the building market, both as regards existing buildings and new buildings. [Spada 2007]

In particular, the air cavity is a very common solution because it solves the problems related to interstitial condensation produced by the difference of the temperature between indoor and outdoor, with a low economic cost. The choice of polyurethane foam panel has been given by the lower price of this material in the market, even if its production involves a high value of CO2 emissions. [Oleotto 2007].

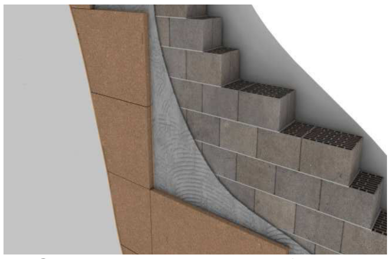
The wood fiber panel is a composed by a very similar material to Opuntia ficus-indica because it is produced from waste materials of the wood industry, and its origin is vegetable, which is also characterized by the presence of lignin, with a value of specific weight very important for thermal lag. However, as already said, it has a high value of CO_2 emissions.

In Tab. 2 it has been possible to compared the different values of: lag of the thermal wave (h), U-value, dynamic thermal transmittance (Yie) and surface mass (Ms), both for the state of the fact that for the proposed intervention through the addition of the different thermal insulating panels.

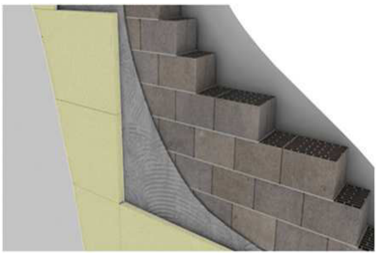


a) Opaque wall (without any insulation).

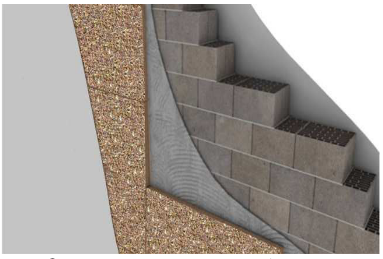
b) Opaque wall with an internal air cavity.



c) Opaque wall with wood fiber panels.



d) Opaque wall with polyurethane foam panels



e) Opaque wall with ficus-indica Opuntia panels.

Fig. 10: Different layers considered for the comparison between possible solutions by the addition, each time, of different 80 mm insulating layers.

Tab.2: The following table contains the main important thermal characteristics of the analyzed external wall, each relating to each stratigraphic combination.

CHARACTERISTICS	CURRENT STATE	1 AIR CAVITY	2 POLYURETHANE FOAM	3 WOOD FIBER	4 FICUS-INDICA OPUNTIA
Wall thickness [cm]	29	37	37	37	37
Total thermal resistance [m^2K/W]	0,98	1,26	3,64	2,93	2,10
Thermal transmittance U [W/m^2K]	**1,02**	**0,79**	**0,27**	**0,34**	**0,47**
Surface mass Ms [kg/m^2]	242	242	245	258	278
Lag of the therma wave [h]	4,45	5,15	6,99	9,80	7,18
Dynamic transmittance Yie [W/m^2K]	1,11	0,75	0,18	0,17	0,33

5 CONCLUSIONS

As shown in Table 2, the different configurations lead to results more or less significant compared to the condition without any insulation, both in terms of thermal transmittance U, periodic transmittance Yie and thermal lag, that have effect on the behavior in summer conditions. The analyzed wall, has an initial thickness of 29 cm and reaches the final thickness of 37 cm after the intervention of insulation energy, with each of the proposed solutions. In all studied cases the thermal transmittance values are flower than the reference value of 1.02 W / m^{2}K. Furthermore, these obtained values are found to be lower than the limit value established by the law, in the case of opaque walls (0,48 W / m^{2}K for zone B, as Palermo). Only in the first case, where it is added to the layer of air in the cavity, there is not a sufficient increase of the thermal performance of the enclosure. As regards the values of thermal lag, the surface mass and periodic transmittance, positive values are obtained which allow to reach a higher thermal behavior, particularly in hot climates. The Opuntia ficus-indica panel allows to obtain a better stratigraphy of the initial condition, with an index of thermal leg equal to 7-18 hours, almost twice the initial one. Moreover, the surface mass, is greater in correspondence of the Opuntia ficus-indica panel, due to its density, the parameter that provides a positive contribution in the calculation of the energy performance of the final stratigraphic composition. An index of surface mass equal to 278 Kg / m^2, in fact, allows to dampen the heat loss through the building envelope that day, ensuring a level of thermal indoor comfort. The performance of the new panel is very similar to the those showed by the commercial panels, contributing, at the same time, to the disposal of waste: the nature of the plant makes the material highly recyclable and easily disposable. Furthermore, the amount of adhesives and/or binders used for the packaging of the panel may be reduced in order to overcome limitations for the disposal of the product. In addition to thermal and ecological advantages, it is also possible to obtain an economic advantage since the production technology carried out for the new proposed panel is similar to that used for the production of insulating panels available on the market. For this reason, the new panel could be easily produced industrially, at a competitive cost because it is easily available. In fact, in Italy the cultivation of prickly pear are localized especially in Sicily, Calabria, Puglia and Sardinia. The most recent statistics attribute to the Sicilian Region, 90% of cultivated areas with an overall size of approximately 2,500 hectares of specialized cultivation and 25,000 hectares of mixed cultivation. As already mentioned, the cladodes of Opuntia ficus-indica showed in Figure 11, can be easily found in Sicily as waste material crop of prickly pears (i.e. fruit of the plant).

In conclusion, the research innovation of the present paper is represented by the type of material used which was not yet applied in the building sector. The proposed panel has great potential both for the large availability of raw material in the basin of the Mediterranean, both for good thermo-acoustic performances reached. Moreover, it worth noting the versatility of application of the panel, which can be extended to several technical elements such as roofs, floors and internal walls for which good insulating performances are needed.

Fig. 11: Opunthia ficus-indica with prickly pear fruits

6 REFERENCES

Anderson EF., The cactus family. Portland: Timber Press; 2001.

Butera D, Tesoriere L, Di Gaudio F, Bongiorno A, Allegra M, Pintaudi AM, Kohen R, Livrea M. Antioxidant activities of sicilian prickly pear (opuntia ficus indica) fruit extracts and reducing properties of its betalains:betanin and indicaxanthin. J Agric Food Chem 2002; 50: 6895-6901.

Cardenas A, Arguelles WM, Goycoolea FM. On the possible role of Opuntia ficus-indica mucilage in lime mortar performance in the protection of historical buildings. J Profess Assoc for Cactus Dev 1998; 3 :64 - 71.

De Vecchi A, Valenza A, Colajanni S, Lanza Volpe A, Fiore V. Materiale isolante a base di cactacee, pannello realizzato con detto materiale e relativo processo di produzione. Italian Patent n. 1402131.

Fassi A. Maina L. L'isolamento ecoefficiente, guida all'uso dei materiali naturali. Nuova edizione aggiornata. Milano: Edizioni Ambiente 2009.

Hegwood DA. Human healthy discoveries with Opuntia sp.(prickly pear). Hort Sci 1990; 25: 1515-1516.

Galati EM. Mondello MR, Giuffrida D, Dugo G, Miceli N, Pergolizzi S, Taviano MF. Chemical characterization and biological effects of sicilian Opuntia ficus indica (L.) Mill. fruit juice: Antioxidant and antiulcerogenic activity. J Agric Food Chem 2003; 51(17): 4903-4908.

Galati EM, Mondello MR, Monforte MT, Galluzzo M, Miceli N, Tripodo MM. Effect of Opuntia ficus-indica (L.) Mill. Cladodes in the wound-healing process. J Prof Assoc Cactus Dev 2003; 5: 1-16.

Garcia Saucedo PA, Valdez Morales M, Valverde ME, Cruz Hernandez A, Paredes L. Plant regeneration of three Opuntia genotypes used as human food. Plant Cell 2005; 80: 215–219.

ISO 8302, Thermal Insulation – Determination of Steady-state Thermal Resistance and Related Properties – Guarded Hot Plate Apparatus, International Organization for Standardization, Geneva.

López R, de Ita A, Vaca M. Drying of prickly pear cactus cladodes (Opuntia ficus indica) in a forced convection tunnel. Energy Convers Manage 2009; 50: 2119–2126.

Malainine ME, Dufresne A, Dupeyre D, Mahrouz M, Vuong R, Vignon MR. Structure and morphology of cladodes and spines of Opuntia ficus indica. Cellulose extraction and characterization. Carbohydr Polym 2003; 51: 77–83.

Malainine ME, Mahrouz M, Dufresne A. Lignocellulosic flour from cladodes of Opuntia ficus indica reinforced poly(propylene) composites. Macromol Mater Eng 2004; 289: 855-863.

Oleotto E., Guida agli isolanti naturali, prodotti, caratteristiche, tipologie d'impiego, Edicom edizioni, Monfalcone (Gorizia).

Rodriguez-Felix A, Soto-Valdez H. Quality chances of diced nopal during storage in polyethylene bags. In: Felker P, Moss JR, editors. Proceedings of the third annual Texas Prickly pear council; 1992, Kingsville, TX. p. 22–25.

Spada C., Isolanti di origine vegetale, tetto e pareti, Cà Zorzi edizioni, Forlì.

Vignon MR, Heux L, Malaininea ME, Mahrouz M. Arabian-cellulose composite in Opuntia ficus-indica prickly pear spines. Carbohydr Res 2004; 339: 123–131.