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Building energy performance: A LCA case study of kenaf-fibres insulation board

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Abstract

The paper presents a life cycle assessment of a kenaf-fibre insulation board following the international standards of the ISO 14040 series. Each life-cycle step has been checked, from kenaf production and board manufacture by an Italian firm, to use and disposal.

The aim is to assess the board eco-profile and to compare, on the basis of a life-cycle approach, the energy and environmental benefits and drawbacks related to its employment into a typical residential dwelling. A comparison among various insulating materials has been carried out.

The study focuses also on processes and input materials which cause the main environmental impacts of the product, and points out critical issues and the life-cycle steps with the highest improvement potentials.

Keywords: LCA; Bio-building materials; Sustainable building

1. Introduction

According to the 2003/87/CE Directive the EU has introduced a scheme for greenhouse gas trading in the Community. The emission trading scheme [ETS] covers about a third of the total greenhouse emissions in the UE-25, deriving from installations as combustion plants, mineral oil refining, coke ovens, iron and steel plants, cement, glass, brick, ceramics, pulp and paper [1].

The building sector, as well as the transport one, is not taken into account by the ETS, although the high energy demand and the long useful life of buildings involve a relevant share in the EU energy balance and in the CO_2 emissions scenario. In fact this sector accounts for about 40% of energy use and greenhouse gas emissions [2]. On average, one-third of energy end-use is consumed for heating, cooling, lighting, appliances and general services in residential, commercial and public buildings. In 2000, an average household in the EU used about 52,000 MJ for heating purposes, corresponding to about 77% of the total average energy consumption per household (67,450 MJ) [3].

The above figures point out the EU need to reduce the building energy consumption, both for advancing in the fulfilment of Kyoto Protocol targets and for reducing its energy dependency. Therefore, the national allocation plan (NAP), in which each member state establishes how the emission rates have to be allocated for the periods 2005–2007 and 2008–2012, should be prepared involving also the building sector. Such a NAP should agree with the Kyoto Protocol target of reduction of the greenhouse emissions and with the final goal to stabilize the air greenhouse gas concentrations at safe levels [2].

The relevant weight of the building sector in the energy balance of each UE country involves the need of regulation and market mechanisms, like the energy certification, to structure the application of energy assessment in the building sector. The Directive 2002/91/CE, in advancement of the action lines showed in the Directive 93/76/CEE for the building sector, establishes a general framework in which the building energy assessment should be implemented [4,5]. The EU member states have to establish minimum energy performance standards and energy certification schemes that allow to drive the building sector to higher energy performance levels, promoting measures of energy efficiency (bioclimatic architecture standards, passive heating and cooling, renewable sources integration, etc.).

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2. The relevance of thermal insulation in the building energy performance

Currently, the total energy consumption of an average Italian household is about 78,219 MJ/year, of which the 80% (62,575 MJ/year) is used for heating and the remaining 20% is used for lighting and appliances, hot water supply, and cooking [6]. In such a context, an appropriate planning for building energy saving should need rational criteria of energy assessment to quantify energy consumption during design, construction and operating time, and suitable strategies and measures to increase building energy performance, such as the reduction of fossil fuels consumption, the growth of renewable energy use, and the energy-efficient conversion [7].

The use of thermal insulation materials in building walls and roofs is the most relevant tool to improve energy performance, reducing the resources consumption and the associated environmental burdens arising from the combustion of fossil fuels. Furthermore, the use of thermal insulation materials reduces the heat losses from buildings, involving considerable energy and cost savings for air conditioning and heating during the building lifetime [8].

The European market of insulation materials is still dominated by two groups of products, which are classified according to their chemical or physical structure [9]:

- mineral or inorganic fibrous materials, namely glass wool and stone wool, which account for 60% of the market;
- organic foamy materials, like expanded polystyrene (EPS), extruded polystyrene (XPS) and the less widespread polyurethane (PUR), which account for about 30% of the market;
- other materials, as combined materials (wood-wool, gypsum-foam) and new technology materials (transparent and dynamic materials), which account for about 10% [10].

Inorganic fibrous materials are expected to play the main role in the next decade, with a production growth of more than 5%, whilst the organic foams will probably have a lower production growth [11].

In spite of that, innovative insulation products have recently emerged on the market. They are based on biological resources and therefore are called biomaterials.

3. Biomaterials requirements in sustainable buildings

Each building product involves environmental impacts in its life-cycle, due to the resources consumption and pollutant releases during the resources extraction, the product manufacturing and use, and the products' end-of-life (collection/sorting, reuse, recycling, and waste disposal) [12].

The use of building biomaterials involves the following environmental benefits during the whole life-cycle [13,14]:

- reduction of resource consumption;
- energy saving and less environmental impacts;
- recovery, re-use and recycling of the products before the final disposal.

There is an increasing interest in using agricultural fibres for building components, either to complement or replace wood, in combination with wood fibres or other materials.

Such interest, associated to the political engagement to control CO_2 emissions, can help the spread of biomass crops in the next years.

In the following it is showed the eco-profile of a thermo-insulating board based on a biomaterial, called ''kenaf-fibre''.

4. Case study: kenaf-fibre board

4.1. Goal and scope definition

The main goal of the study is to define the energy and environmental profile of an insulation product based on a natural fibre composite material. The analysis is carried out according to the Life Cycle Assessment (LCA) standards of the series ISO 14040 [15–18].

4.2. Kenaf properties

The assessed product is a fibre reinforced composite made by kenaf vegetable fibres which are incorporated in a polyester matrix. Kenaf (*Hibiscus cannabinus*) is a herbaceous annual plant that grows very quickly under a wide range of weather condition. It grows more than 3 m in 3 months even in moderate ambient conditions [19]. Kenaf is cultivated in Italy and other Mediterranean countries and mainly used in the thermal insulation field and in the pulp production.

Kenaf has been actively cultivated in recent years essentially for the following reasons [20]:

- it needs few treatments during the growth as, for example, low quantities of chemical fertilizers;
- kenaf absorbs CO_2 at a significantly high rate.

Kenaf exhibits low density, non-abrasiveness during processing, high specific mechanical properties, and biodegradability. Recently, kenaf has been used as a raw material alternative to the wood in pulp and paper industries, and in the textile industry [21].

Thermal conductivity and resistance are distinctive properties of an insulating board since they relate to the heat flow through a composite board. Thermal conductivity should remain unvaried in the board lifetime. However, it could increase depending on moisture and chemical and physical deterioration of the material. Therefore, the following basic properties are relevant in the insulation materials lifetime:

- durability, since the material must be stable to moisture and resistant to biological attack;
- ignition behaviour [22].

4.3. Functional unit

According to the ISO 14040 standard the functional unit (f.u.) is defined as the reference unit through which a system performance is quantified in a LCA.

In this study, f.u. is defined as the mass (kg) of insulating board which involves a thermal resistance R of 1 (m^2 K/W), according to a proposal of Council for European Producers of Materials for Construction [23]:

$$\text{f.u.} = R\lambda\rho A \tag{1}$$

where R is the thermal resistance as 1 m^2 K/W; λ the thermal conductivity measured as W/(m K); ρ the density of the insulation product in kg/m^3; A is the area as 1 m^2.

Such a functional unit gives information about the amount of insulation material required to perform a given thermal resistance during the insulation lifetime, focusing only on the environmental and insulating properties of the assessed material. According to the Eq. (1) and the thermo-physical properties showed in Table 1, the f.u. corresponds to an insulation board of 1.52 kg.

4.4. Description of the production system

The material is cropped, pressed into bales, and transported to the plants. First, kenaf fibres are analyzed, evaluating quality, weight, moisture, impurities and maceration condition, and after that they are stored. Then, a belt conveys the bales of kenaf to the cleaning process.

Proper machines remove cortical and ligneous parts from stalks. The residues are collected on a second belt and conveyed to the pellets production phase. Such pellets are used in the nearest thermoelectric power stations.

The cleaning process is completed with the removal of dust from the fibres, which can be now conveyed to the manufacturing process. The clean fibres represent about 30% of the input material, while the remaining part is composed by residues (60%) and dust (10%).

Finally, thermo-fusible polyester resins are added as binder of the basis fibres and the resulting compound is conveyed into a furnace. Its temperature is regulated between 160 and 180 °C to allow the fusion of polyester fibres. Depending on the required density, thickness and size, the insulation board is addressed to a proper moulding machine. In detail, kenaf fibres represent the 85% of the total mass, while polyester fibres represent the remaining 15%.

4.5. Definition of the system boundaries

In this study energy and mass flows and environmental impacts have been assessed from the production of raw materials to the manufacture of the end-product, following the "*cradle to gate*" approach. The following life-cycle steps have been analysed [16]:

- *Cultivation and crop of kenaf*. Production of kenaf plants takes place mainly in Italy. Fibres are also partially bought from foreign Mediterranean countries (in particular from Morocco). Data regarding the consumptions of fertilisers and diesel have been detected during an Italian average cultivation cycle. Water consumptions are not detected during the cultivations.
- *Transports along all phases*. It has been assumed that national transports occur by road lorry. Cargo ships are employed for international transports from Mediterranean countries.
- *Kenaf fibres refining and manufacturing of the insulation board*. A typical production cycle from an Italian factory has been monitored.
- *Installation, maintenance and use*. Concerning installation and maintenance, impacts are neglected. In fact, the insulation board is installed by hand, and does not require maintenance when it is incorporated in the wall. Regarding the use phase, the primary energy saving and the avoided CO_{2eq} emissions have been estimated during the operation time.
- *End of life*. Concerning to the disposal phase, the option of incineration[1] is assumed. The CO_2 emissions from the combustion of the kenaf fibres have been not taken into account. In fact the combustion of biomass does not increase the greenhouse effect, since the amount of CO_2 emitted during the combustion is assumed to be equivalent to the amount of CO_2 which is captured during the growth.

Environmental impacts of energy sources have been referred to the national and international environmental databases [24–26].

4.6. Quality of data and inventory phase

The inventory phase started from the analysis of the production process of the kenaf board. Data refer to an exemplary Italian firm that can be assumed as representative of the Italian production sector. Successively the analysis has been focused on the production and transport of kenaf fibres and other system's components. Data have been collected by in-field enquiry and bibliographical references.

From local investigation the following data were obtained:

- amount of annual cropped kenaf and of chemical fertilizers consumed in the kenaf growing;
- fuel consumption per hectare of kenaf cultivation and crop;
- electricity and methane consumption in the process of insulating boards production;
- amount of polyester resins added in the production process;
- amount of organic wastes and dusts derived from the process.

Table 1
The functional unit (kg) needed to provide a thermal resistance of 1 (m^2 K/W)

Kenaf properties		
λ	W/m K	0.038[a]
ρ	kg/m^3	40[a]
s	mm	38
f.u.	kg	1.52

[a] Producer information.

[1] The electricity produced during incineration has been not considered as a benefit in the environmental profile of the product.

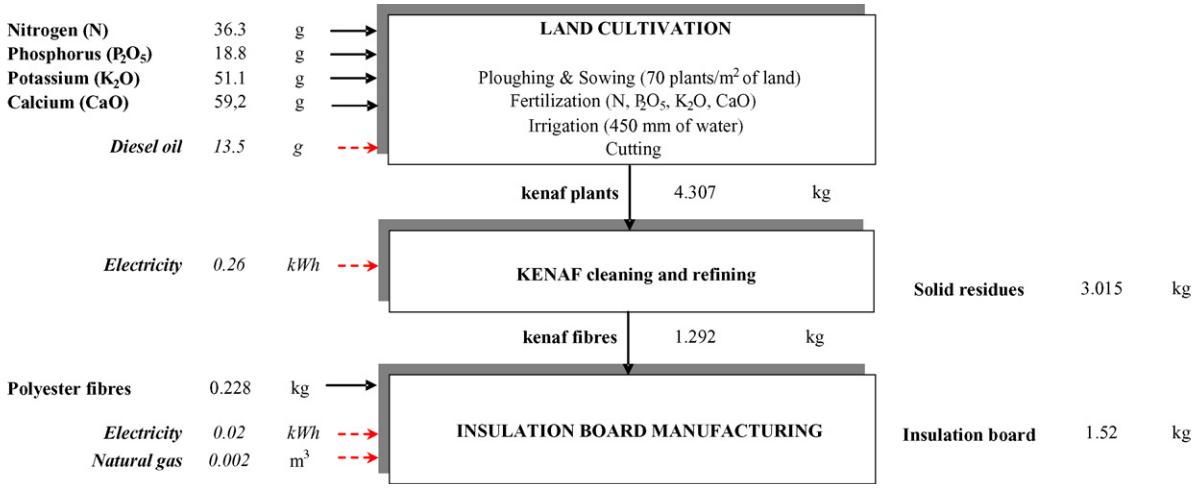


Fig. 1. Flow chart of the production system.

Fuel consumption and air emissions in the transport steps are estimated, depending on the transport modes and the distance among sites. In detail, the following modes are assumed:

(1) road haulage by diesel lorry with maximum capacity of 16×10^3 kg;
(2) sea freight by cargo ship with maximum capacity of 1000×10^3 kg.

International databases have been used to calculate the eco-inventories of raw materials and energy sources. In particular, the eco-profiles of methane boiler and transports are derived from [24]. The environmental impacts due to polyester fibres production, the Italian electricity mix and the impacts due to the use of methane are derived from [25], while the eco-profiles of chemical fertilizers and electricity of foreign countries are derived from [26].

Fig. 1 shows inputs and outputs flow chart related to the cultivation and the production process. Regarding the FU disposal, no data are available. In fact, the firm started production of kenaf boards a few years ago and, consequently, the installed boards have not yet reached their end-life. Data regarding disposal come from estimations. Environmental impacts of incineration are derived from [24].

4.6.1. Allocation

Allocation of raw materials and energy sources is carried out according to mass and economic criteria as following described:

1. The company employs electricity to refine the kenaf fibres and, successively to manufacture the insulation boards. Following the company's suggestions, it can be supposed that about 60% of the electricity is consumed to process the fibres while the 40% is used to manufacture the panel.[2]
2. The industrial treatment of kenaf biomass involves the use of electricity for the grinding and refining phases. Kenaf fibres and vegetable residues are the outputs of these processes. The fibres represent the main output and they are addressed to the insulation board production, while the residual parts are by-products employed for the production of refuse derived fuels (RDF). Residuals represent the highest fraction (70%) of the total treated mass having, however, a low economic value. Consequently, a mass criterion for allocation of electricity impacts during these phases would be related to the residuals, in spite of the effective secondary role that the residues play in the company earnings. Therefore, environmental impacts due to such a process are allocated according to the economic criterion.[3] A similar procedure has been applied to the allocation of diesel and fertilizers employed during the cultivation.
3. Methane is employed into furnaces for panel's production. The furnaces are alternatively used by the firm for the production of various typologies of insulation boards. A mass based allocation of methane consumptions to kenaf boards is carried out, taking into account the annual kenaf board mass production in relationship to the overall board production.

4.6.2. Results

The inventory results for the f.u. are presented in Table 2.

Results show that the Global Energy Requirements (GER)[4] is 59.37 MJ_{Prim}/f.u. In particular, the introduction of polyester fibres as filler of the kenaf insulation board involves a high energy consumption (about 35% of the GER). Worth of note is that about 38% of the whole energy consumption is represented by renewable energy sources (biomass). Such a result can be

[2] This estimation is based on the analysis of the power of machines and of the working times.

[3] The residues that have an economic value represent about 20% of kenaf mass.

[4] The GER represents the energy demand that arises in connection with the production from raw materials to final product [28].

Table 2
Life-cycle inventory results per functional unit

Energy consumption	Unit	Quantity
Energy use	MJ	28.38
Feedstock, fossil	MJ	8.82
Feedstock, renewable	MJ	22.17
Total energy consumption	MJ	59.37
Water consumption		
Water	kg	10.7
Air emissions		
Dust	g	429
CO	g	8.9
CO_2	g	2.908
SO_x	g	14.6
NO_x	g	17.2
N_2O	g	0.5
Methane	g	3.8
HF	g	0.004
HCl	g	0.13
Metals	g	0.052
Ammonia	g	0.33
VOC	g	1.26
Water emissions		
COD	mg	967
BOD	mg	216
Dissolved solids	mg	13
Suspended solids	mg	3.889
Hydrocarbons	mg	40
Phenol	mg	13
Na^+	mg	760
NH^{4+}	mg	3
Phosphate as (P_2O_5)	mg	1
Dissolved organics	mg	2.450
Nitrogenous matter	mg	1
Solid waste		
Mixed municipal solid waste	kg	1.73
Inert minerals/metal	kg	0.24
Slag/ash	kg	0.04
Residues/by-products		
Vegetable residues	kg	3.00

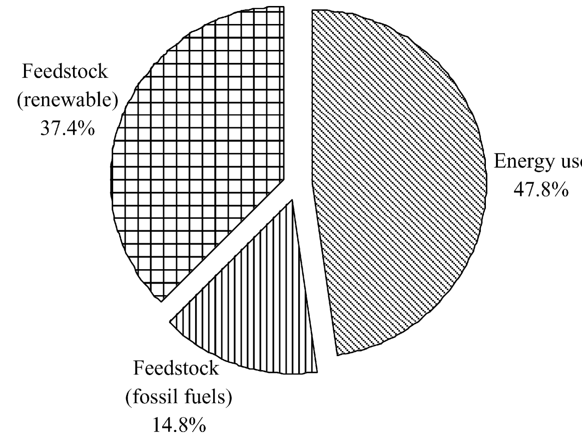


Fig. 2. Sharing of energy consumption in the kenaf board production.

Table 3
Impact analysis results per f.u.

Impact category	Unit	
Global energy requirement (GER)	MJ_{Prim}	59.37
Global warming potential (GWP)	kg CO_{2eq}	3.17
Acidification potential (AP)	g SO_{2eq}	27.4
Nutrification potential (NP)	g $PO_4{}^{3-}{}_{eq}$	2.4
Phochemical ozone creation potential (POCP)	g C_2H_{4eq}	2.2
Ozone depletion potential (ODP)	kg CFC-11_{eq}	Negligible
Water consumption	kg	10.7
Total wastes	kg	2.0

viewed as one of the environmental benefits brought by the board production.

Besides, more than half of the energy use is represented by the feedstock[5] (Fig. 2) and, therefore, it is partly recoverable when incineration with energy recovery is assumed as a disposal option of the board at the end-life.

4.7. Impact assessment

The inventory phase shows the disaggregated data related to the f.u. These results are, however, not easy to manage especially if the aim is the comparisons of replaceable products. Therefore, inventory data are processed, aggregated and classified in impact categories related to the most relevant environmental issues [27].

Characterization factors[6] lead to assess the contribution that input and output data bring to potential environmental impacts. The contribution to the following impact category has been assessed:

- global energy requirement (GER);
- global warming (GWP);
- photochemical ozone creation potential (POCP);
- nitrification (NP);
- acidification (AP);
- ozone depletion potential (ODP);
- water consumption;
- waste generation.

Results of the impact assessment are presented in Table 3.

Greenhouse gas (GHG) emissions represent the main environmental release in the board life-cycle, accounting for about 3.17 $kg_{CO_{2eq}}$ per f.u. Fig. 3 shows the shares of the life-cycle phases to the total GHG emission. The highest share is caused by the manufacture of input materials and, in particular, of the polyester fibres, which account for about 39% of the total. Transports account for 23%, while the final disposal accounts

[5] Feedstock is defined as *heat of combustion of raw material inputs*, *which are not used as an energy source*, *to a product system* [16]. The feedstock quantifies the potential of materials (as wood or plastics) to deliver energy when they are burned with heat recovery after their useful life.

[6] *Characterisation factor*: *factor derived from a characterisation model*, *which is applied to* convert the assigned LCI results to the common unit of the category indicator [17].

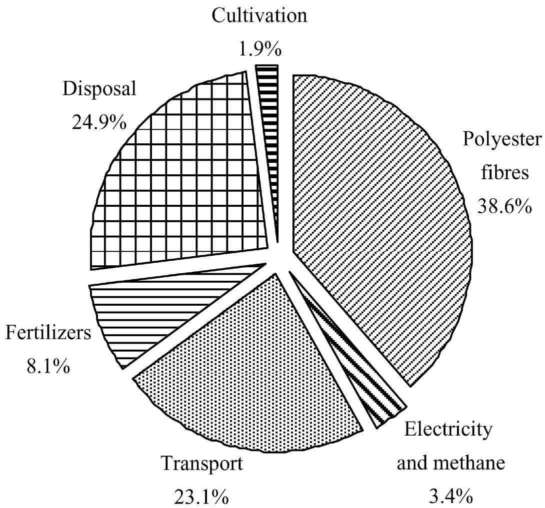


Fig. 3. Sharing of greenhouse gas emissions in the kenaf board life-cycle.

for 25% of the total GHG emission, because of the combustion of the polyester fibres.

Total generated wastes and residues are about 2.0 kg per f.u. This quantity does not include the vegetable residues due to the fibres processing. These residues have been considered as by-products of the process because they are not disposed but addressed to external companies for the production of RDF. Other wastes are essentially non-hazardous materials mainly derived from the production of raw materials.

4.8. Comparison with other insulation materials

The life-cycle impacts of kenaf board have been compared to the performances of replaceable products. The comparison has included various typologies of mineral, synthetic and natural fibre composites, as following described:

- *Stone wool*. Insulation product based on natural minerals and recycled post-production waste materials, mixed with binder and impregnation oil (density 32 kg/m^3; conductivity 0.037 W/m K). Life-cycle data derive from [25,26].
- *Paper wool*. Insulation based on shredded newsprint paper, mixed with aluminium hydroxide, borax and/or boric acid (density 32 kg/m^3; conductivity 0.040 W/m K). Life-cycle data derive from [25,26].
- *Flax rolls*. Based on flax grown in Europe, mixed with polyester, diammonium hydrogen phosphate and borax (density 30 kg/m^3; conductivity 0.042 W/m K). Life-cycle data derive from [25,26].
- *Polyurethane* (*PUR*). Rigid foam, blown with CFC-free gas (density 35 kg/m^3; conductivity 0.024 W/m K). Life-cycle data derive from [25].
- *Glass wool*. Low-density insulation derived from waste glass, mixed with other minerals and organic resins and melted in electrical furnaces (density 20 kg/m^3; conductivity 0.05 W/m K). Life-cycle data derive from [26].
- *Mineral wool*. Mineral wool derived from basalts and dolomites (density 40 kg/m^3; conductivity 0.04 W/m K). Bonding agents (resins) and impregnating agents sprays (of petroleum products) are added. Life-cycle data derive from [26].

Table 4 and Fig. 4 show the comparison of energy and environmental performances of the different insulation materials. It can be noted that:

- The synthetic PUR foam has the largest impacts in terms of consumed energy and air releases. This is due to the large use of fossil fuels during the production process. The lowest energy consumption is ascribed to the mineral wool.
- Regarding the other environmental categories, paper wool has the best performances.
- The environmental impacts of insulation boards are also largely due to the employment of oil derived resins and binders during the production even in natural-fibre based products. The impacts could be decreased by using recycled products.
- Kenaf board causes a relative large energy consumption (59.4 MJ/f.u.) that is 40% due to renewable feedstock energy (energy content of vegetable fibres). This energy can be partially recovered during incineration.
- The production of kenaf board has a high global warming potential. It must be pointed out that the analysis has not computed the CO_2 absorbed during the plants cultivation,

Table 4
Energy and environmental comparison of insulation materials

		Kenaf	Stone wool	Flax	Paper wool	PUR	Glass wool	Mineral wool
Energy consumption								
Energy use	MJ	28.4	17.4	26.9	11.8	57.6	39.9	25.0
Feedstock, fossil	MJ	8.8	2.5	7.5	0.4	36.0	7.4	0.2
Feedstock, renewable	MJ	22.2	0.9	15.3	14.0	0.0	0.0	0.0
Total	MJ	59.4	20.8	49.7	26.2	93.6	47.3	25.2
Environmental impact indexes								
Global warming potential	kg CO_{2eq}	3.2	1.45	2.36	0.82	3.2	2.2	1.7
Acidification potential	g SO_{2eq}	27.4	12.3	17	5.5	27.9	8.4	4.9
Nutrification potential	g $PO_4{}^{3-}{}_{eq}$	2.4	1.16	1.22	0.7	2.94	1.30	0.8
Photochemical ozone creation potential	g C_2H_{4eq}	2.2	4.6	0.5	0.2	1.4	2.5	3.7
Water consumption	kg	10.7	3.9	5.7	0.8	297.7	27.0	25.6
Wastes								
Total wastes	kg	2.0	0.054	0.122	0.032	0.32	6.6	2.7

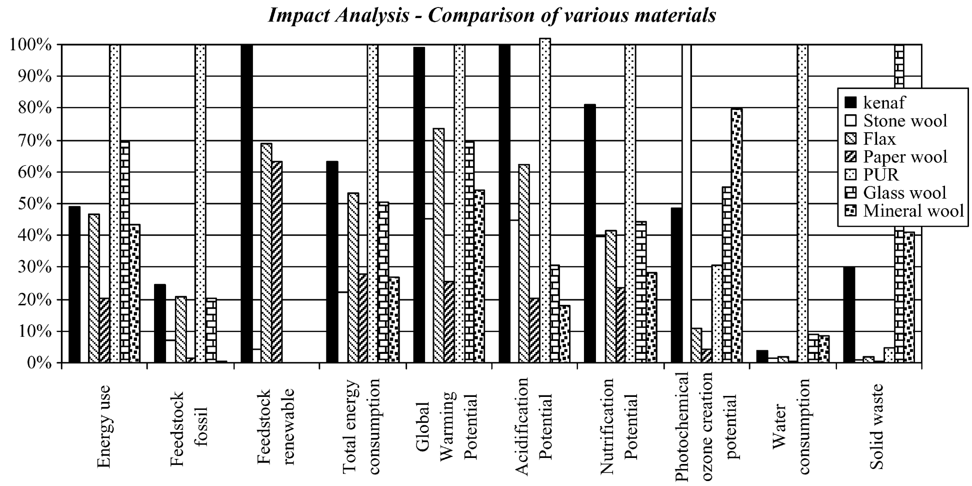


Fig. 4. Comparison of various insulation materials.

assuming that the board will be incinerated at the end of life. No energy recovery from incineration has been accounted. Furthermore, vegetable residues have been computed as process wastes, not considering their large energy contents potentially recoverable.

- Eco-profiles have sensible differences with regard to water consumption and waste production. These differences depends on to the different way of accounting impacts by the used databases. For example, the large water consumption of PUR derives from the accounting of water as cooling circuits, while data from GEMIS database show a large waste production due to the accounting of debris and inert materials from mining.

The comparison has not accounted the human effects due to the exposure to product's air releases. In the last years, stone and glass wools have been suspected to be responsible of severe health risk. However the IARC (the International Agency for Research on Cancer) has reviewed the carcinogenicity of man made mineral fibers in 2002 [29,30]. The IARC monographs working group concluded that only the more bio-persistent materials remain classified by IARC as possible human carcinogens.[7] The commonly used vitreous and mineral fibre wools are bio-soluble and are considered not classifiable as carcinogenic for humans. For these products only the risk phrase R38 (irritating to the skin) remains, considering the mechanical irritation, mainly during manufacture and installation, comparable with exposure of the skin to straw, grass or hay.

Polyurethane foams are not classifiable as carcinogenic for humans [31]. No data are available regarding the effects to the exposure to vegetable fibers as kenaf or flax.

The assessment and the comparison of eco-profile showed the relevance of initial assumptions and accounting methods during the inventory phase. In particular allocation rules, recycling and disposal scenarios could play a key role. These aspects are further discussed in the following paragraph.

5. Sensitivity analysis

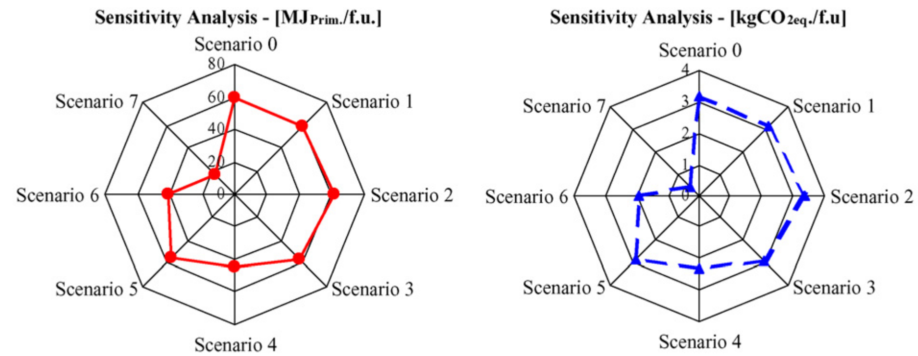
The life cycle assessment (LCA) is a useful tool to estimate the effective energy and environmental impacts related to products or services. However, the results of LCA do not represent "exact" and "precise" data, but are affected by several uncertainty sources. Sensitivity analysis (SA) is a systematic procedure which aids to assess the effects of the chosen methods and data on the outcome of a study. SA can be applied with either arbitrarily selected ranges of variation, or variations that represent known ranges of uncertainty.

In the presented study the inventory analysis has shown that the larger impacts in terms of energy consumption and CO_2 emissions are due to the use of raw materials (synthetic fibres and fertilizers), the consumption of fossil fuels (during cultivation, transports and manufacturing) and the disposal phase.

To state the incidence of these parameters on the eco-profile, initial assumptions have been revised following a scenario analysis. First, assumptions regarding the allocation rules have been modified and three scenarios have been supposed:

- *Scenario 1*. To allocate the electricity consumed during the manufacturing process (40% due to the process of fibres refining and 60% related to the next treatments for the insulation boards production).
- *Scenario 2*. To allocate the consumption of raw materials, diesel and electricity during the cultivation and the fibres refining entirely to the kenaf, neglecting the production of other vegetable residues. These residues are supposed process wastes.
- *Scenario 3*. To allocate raw material, diesel and electricity during the cultivation and the fibres refining following a mass allocation process. Kenaf fibres and residues are considered as equally worth products.

[7] These include refractory ceramic fibres, which are used industrially as insulation in high-temperature environments such as blast furnaces, and certain special-purpose glass wools not used as insulating materials.



		Scenario							
		[0]	***[1]***	***[2]***	***[3]***	***[4]***	***[5]***	***[6]***	***[7]***
Energy	[MJ_{Prim}]	59.4	59.0	61.5	57.0	45.0	55.6	41.0	17.2
Global Warming	[kg $CO_{2eq.}$/f.u.]	3.17	3.15	3.37	2.94	2.32	2.88	1.93	0.36

Fig. 5. Comparison of sensitivity scenarios.

Regarding the employment of synthetic raw materials, Fig. 3 shows the incidence of polyester fibres on the global life-cycle impacts. Data concerning the eco-profile of polyester are reliable and representative of the European production context [25]. Consequently, uncertainty due to the employment of these data is low. On the other side, the sampled firm points out to modify the production process employing recycled polyester fibres (mainly residues from neighbour textile companies). Many researches showed that the recycled plastics have sensible lower environmental burdens compared to virgin plastics (for instance, the energy consumption decreases from 50% to 90% [32–34]). Scenario 4 calculates the eco-profile of the kenaf board supposing to reduce the impacts of polyester fibres by 70%.

The transport phase includes the transport of raw materials, the delivery of the products to the final user and the end-life transportations. However, a large part of kenaf is purchased from foreign Mediterranean countries and delivered by truck or ship. The transport of kenaf plants to the manufacturing site represents the dominant step of the transportation phase. Transport scenario has been modified supposing all the plants produced in Italy with an average distance for transports of 400 km double way (Scenario 5).

The disposal phase supposed the manual removal of the boards from the building walls, their transport and disposal to a neighbouring incinerator. Two new disposal scenarios have been supposed:

- to incinerate the board including the recovered energy[8] in the eco-profile (Scenario 6);
- to incinerate the board and the biomass residues, including the recovered energy in the eco-profile (Scenario 7). This scenario is the composition of Scenarios 2 and 6, with the inclusion of the incineration of residues.[9] This disposal strategy allows the global production of 15.9 MJ of electricity.

The sensitivity analysis has been performed on the energy consumption and greenhouse gases. Results are showed in Fig. 5, where Scenario 0 indicates the normal eco-profile as represented in the previous paragraphs. The analysis shows that:

- the global energy consumption varies from 17.2 to 61.5 MJ_{Prim}/f.u.; the global warming potential from 0.36 $kg_{CO_{2eq}}$/f.u. to 3.37 $kg_{CO_{2eq}}$/f.u.;
- the largest variations are due to the modifications in the disposal assumptions (Scenarios 6 and 7). In particular, the energy recovery and the inclusion of the electricity production in the eco-profile can reduce the energy consumption of 30 ÷ 90%;
- the employment of recycled fibres reduces the environmental impacts impact of 30%;
- assumptions regarding the allocation rules and the transports have a small incidence (about ±10%). In particular, Scenario 1 involves very low variations, while use of local national productions (Scenario 4) can decrease of 9% the CO_2 emissions;
- Scenario 2 is the only one that involves an increment of environmental burdens. All the other scenarios foresee an improvement of the kenaf board's performances.

Therefore, the eco-profile of the insulation board can be sensibly modified by including in the life-cycle balance the

[8] The incineration of the insulation board allows the production of 6.14 MJ of electricity (estimation from Italian environmental database [24]). This quantity is considered as an environmental "credit" in the LCA, substituting the electricity produced from a conventional plant. The eco-profile of thermal electricity generation refers to Boustead database [25].

[9] This scenario is realistic, being the vegetable process residues used for the production of Refuse Derived Fuel (RDF).

energy recovery during incinerations. That shows the need to start up a recovery strategy at the end of life of the building. Furthermore, if the process residues were employed as alternative fuel for the electricity generation, the energy and environmental burdens of the board would be reduced to the quarter (one-fourth). In such a case, the performances of the kenaf board would be more ''attractive'' than all the other considered mineral and synthetic insulations.

6. Environmental benefits during building operation

The heating cost in a residential building depends not only on the volume to be heated, the climate and the desired internal temperature, but also on the heat losses through walls and roofs. According to the Italian regulation [35], the main purpose of insulation materials is to decrease the heat loss from buildings and to save energy and costs. During the lifetime of a building the energy savings will be considerable and much higher than the energy consumption during the material's life-cycle. The energy and environmental benefits related to the employment of kenaf boards in typical dwelling[10] have been assessed.

The primary energy saving during the winter has been estimated by means of the following formula:

$$E_{\text{saved,win}} = \frac{3,6F(1/R_i - 1/(R_i + s/\lambda))DD \times S \times 24n}{1000\eta} \qquad (2)$$

where: $E_{\text{saved,win}}$ (MJ) represents the saved primary energy in the winter period (December 1st–31st March); F/η is the conversion factor of primary energy for methane, including the efficiency η of domestic boiler [23]; n represents the operating time of the building; R_i (m^2 K/W) is the thermal resistance of wall without insulation; s (m) and λ (W/m K) are thickness and thermal conductivity of the insulation board, respectively; S (m^2) is the overall area of the walls; DD (K g) are degree day figures for the city where building is located; 24 (h/day) is the daily hours number of building heat loss.

An energy saving of about 2481 MJ_{Prim}/f.u. is estimated in the building operating time, fixed in 30 years. This saving reaches the maximum in the Scenario 7, in which it is about 150 times higher than the global energy consumption in the production of the kenaf board (GER: 17.2 MJ/f.u.). The lowest energy saving is associated with the Scenario 2, in which it is about 50 times higher than the global energy consumption in the production of the board (GER: 61.5 MJ/f.u.).

The avoided CO_{2eq} emissions in the overall life-cycle are estimated about $135.24\,\text{kg}_{CO_{2-eq}}/\text{f.u.}$

7. Conclusion

In this paper an eco-profile of the kenaf-fibre thermal insulation board has been defined and, on the basis of a life-cycle approach, the energy and environmental benefits and drawbacks associated with its use into residential buildings have been assessed.

The results show that the use of natural fibres involves a significant reduction of the environmental impacts derived from the employment of synthetic insulating materials, maintaining high thermo-physic and noise-abatement properties.

The life-cycle impacts of kenaf board have been compared with the performances of various replaceable products, as polyurethane, glass wool, flax rolls, stone wool, mineral wool and paper wool. Such a comparison shows that the highest impacts are related to synthetic materials, while the better performances are due to mineral wools. However, the kenaf-fibre based products become widely the less impacting ones if different disposal scenarios are adopted. In particular, the incineration with energy recovery and electricity production could decrease the global energy requirements of f.u. to 17 MJ. A further reduction can be obtained with the introduction of recycled materials into the manufacture process or with the local production of kenaf plants.

Finally the energy saving during the building operating time results largely higher than the global energy consumption related to the board life-cycle.

This confirms the large energy and environmental advantages related to the employment of insulating materials.

This study shows as the overall energy impact of the building could be more easily evaluated with a life cycle analysis approach. Embodied energy data and life cycle analysis should be included in energy certification schemes in order to effectively lead the building sector toward sustainability. The life-cycle thinking approach seems to be more ''reliable'' with regard to the achieved results, encompassing all the life phase of the building. Therefore it is surprising that even nowadays LCA is not considered in the most advanced building energy legislation.

[10] Flat of 150 m^2 floor surface with external walls, constituted by normal bricks and plaster.

References

[1] Directive 2003/87/CE of the European Parliament and of the Council of 13 October Which Establishes a Scheme for Greenhouse Gas emissions Trading within the Community, Modifying the Directive 96/61/CE of the Council, 2003.

[2] X. Garcìa-Casals, Analysis of building energy regulation and certification in Europe: their role, limitations and differences, Energy and Buildings 38 (5) (2006) 381–392.

[3] U.N.E.P., Sustainable building and construction, Industry and Environment 26 (2/3) (2003).

[4] Directive 2002/91/CE of the European Parliament and of the Council of 16 December 2002 on the Energy Performance of Buildings, 2002.

[5] Directive 1993/76/CEE of the Council of 13 December 1993 on the Limitation of the Carbon Dioxide Emissions Through the Improvement of Energy Efficiency (SAVE), 1993.

[6] ENEA, Report on Energy and Environment 2003. Part 2 Ed. ENEA, February 2003 (in Italian language).

[7] M. Beccali, M. Cellura, M. Mistretta, Environmental Effects of the Sicilian Energy Policy: The Role of Renewable Energy, currently waiting to be published on Renewable and Sustainable Energy Reviews, Elsevier.

[8] M. Zimmermann, Althaus, H.-J. Haas, Benchmarks for sustainable construction. A contribution to develop a standard, Energy and Buildings 37 (11) (2005) 1147–1157.

[9] A.M. Papadopoulos, State of art in thermal insulation materials an daims for future developments, Energy and Buildings 37 (1) (2005) 77–86.

[10] A.M. Papadopoulos et al., Design and Development of Innovative Stonewool Products for the Energy Upgrading of Existing and New Buildings, Project Interim Report, Thessaloniki, 2004 (in Greek).
[11] C.R. Gentle, M.R. Lacey, Design of a novel insulated construction material, Materials and Design 20 (6) (1999) 311–315.
[12] G. Rebitzer, T.R. Ekvall, D. Frischknecht, Hunkeler, G. Norris, T. Rydberg, W.-P. Schmidt, S. Suh, B.P. Weidema, D.W. Pennington, Life cycle assessment. Part 1: framework, goal and scope definition, inventory analysis, and applications, Environment International 30 (2004) 701–720.
[13] C.S. Anders, A.J. Allan, U.C. Anders, Ole Kamstrup and Dennis Postlethwaite, a comparative life cycle assessment of building insulation products made of stone wool, paper wool and flax. Part 1, The International Journal of LCA 9 (1) (2004) 53–66.
[14] C.S. Anders, A.J. Allan, U.C. Anders, Ole Kamstrup and Dennis Postlethwaite, a comparative life cycle assessment of building insulation products made of stone wool, paper wool and flax. Part 2, The International Journal of LCA 9 (2) (2004) 122–129.
[15] ISO 14040, Environmental Management: Life Cycle Assessment: Principles and Framework, International Organisation for Standardisation, Geneva, 1997.
[16] ISO 14041, Environmental Management: Life Cycle Assessment: Goal and Scope Definition and Inventory Analysis, International Organisation for Standardisation, Geneva, 1998.
[17] ISO 14042, Environmental Management: Life Cycle Assessment: Life Cycle Impact Assessment, International Organisation for Standardisation, Geneva, 2000.
[18] ISO 14043, Environmental Management: Life Cycle Assessment: Life Cycle Interpretation, International Organisation for Standardisation, Geneva, 2000.
[19] T. Nishino, K. Hirao, M. Kotera, K. Nakamae, H. Inagaki, Kenaf reinforced biodegradable composite, Composite Science and Technology 63 (9) (2003) 1281–1286.
[20] T. Seller, Jr., N.A. Reichert (Eds.), Kenaf Properties, Processing, and Products, Mississippi State University, Mississippi, 1999.
[21] S. Amaducci, M.T. Amaducci, R. Benati, G. Venturi, Crop yield and quality parameters of four annual fibre crops in north of Italy, Industrial Crops Products 11 (2/3) (2000) 179–186.
[22] Council Directive 89/106/EC, Classification of the Reaction to Fire Performance of Construction Products, Official Journal of the European Communities, 2000/147/EC.
[23] CEPMC, Guidance for the Provision of Environmental Information on Construction Products, Council for European Producers of Materials for Construction, Brussels, 2000.
[24] Italian Agency for Environment Protection (ANPA), Italian Data Bank as Support of Life Cycle Assessment, Database LCA, Ver. 2.0, 2000 (in Iatalian language).
[25] The Boustead Model, Black Cottage, UK. Environmental Database, Ver. 4. 4, Boustead Consulting Ltd., West Sussex, 2001.
[26] GEMIS, Öko-Institut (Institut für angewandte Ökologie—Institute for Applied Ecology) Global Emission Model for Integrated Systems (GEMIS), German Environmental Database. Version 4.3.
[27] Italian Agency for Environment Protection (ANPA), Rules for Environmental Product Declaration, July 2001 (in Italian language).
[28] VDI Richlinie 4600, Kumulierter Energieaufwand, Verein Deutscher Ingenieure, 1997.
[29] IARC, International Agency for Research on Cancer, Some monomers, plastics and synthetic elastomers, and acrolein—summary of data reported and evaluation, IARC, Monographs on the Evaluation of Carcinogenic Risks to Humans 19 (Suppl. 7) (1987).
[30] IARC, International Agency for Research on Cancer. Man-made Mineral Fibres and Radon—Summary of Data Reported and Evaluation, IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, vol. 43, 2002.
[31] IARC, International Agency for Research on Cancer. Man-Made Vitreous Fibres—Summary of Data Reported and Evaluation, IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, vol. 81, 2002.
[32] S. Ross, D. Evans, The environmental effect of reusing and recycling a plastic-based packaging system, Journal of Cleaner Production 11 (2003) 561–571.
[33] V. Krivtsov, P.A. Wäger, P. Dacombe, P.W. Gilgen, S. Heaven, L.M. Hilty, C.J. Banks, Analysis of energy footprints associated with recycling of glass and plastic—case studies for industrial ecology, Ecological Modelling 174 (2004) 175–189.
[34] A.C. Woolridge, G.D. Ward, P.S. Phillips, M. Collins, S. Gandy, Life cycle assessment for reuse/recycling of donated waste textiles compared to use of virgin material: an UK energy saving perspective, Resources Conservation and Recycling 46 (2006) 94–103.
[35] Rules for the Italian National Energy Master Plan accomplishment, Ordinary Supplement to Official Gazette, No. 13, 1991, 16 January (in Italian language).

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