Building insulation materials from agricultural by-products

Current utilization methods and possibilities in Hungary

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Abstract—**One of the most important research topics nowadays to provide adequate solutions for supporting sustainability in architecture and building construction. Reducing fossil fuel consumption and CO2 emission represents the priority which forms also a challenge for the building materials industry. The treatment and disposal of the year-by-year regenerated large amounts of agricultural by-products, is also a major problem, because most of the common processes (e.g., their incineration as biomass or biofuel) involve significant emission of pollutants (e.g., greenhouse gases). Utilization of agricultural by-products in building industry offers a good opportunity, as it can simultaneously provide a source of renewable raw materials and reduce greenhouse gas emission by incorporating the bound CO2 that was removed from the atmosphere by the living plant. The main purpose of this paper is to summarize up-to-date knowledge about the latest international research results at an extensive information platform in order to be recognized its importance by a wide professional audience and realize the current world-wide methods, trends and possibilities which could be adapted taking into account the special Hungarian agricultural traditions and climatic conditions.**

Keywords—thermal insulation; by-product; agriculture; building material; bio-architecture

I. Introduction

One of the most important research topics nowadays to provide adequate solutions for supporting sustainability in architecture and building construction. Reducing fossil fuel consumption and CO2 emission represents the priority which forms also a challenge for the building materials industry.

Building sector is responsible for a very significant part (over 40%) of the global energy consumption; furthermore, for 56.7% of CO2 emission, which is considerable [1][2]. To reduce these high levels of energy consumption and emissions, limitations about the amount of energy used in building materials production and thermal insulation performance of buildings have to correspond increasingly stringent standards and regulations, forcing architects to design and apply sustainable methods and renewable-based materials for thermal insulation.

Another major problem is the treatment and disposal of the year-by-year regenerated large amounts of agricultural by-products, because most of the common utilization methods (e.g., incineration as biomass or biofuel) involve significant emission of pollutants (e.g., greenhouse gases).

Worldwide, including Hungary, cereal straw (wheat, rye, barley, oats) is the only one, of which 60% is harvested for animal bedding, cellulose production, making mushroom compost or biomass [3]. This proportion is only 6-7% in the case of cornstalk [4] and sunflower stalk, while rapeseed straw harvesting is almost non-existent [5]. At best these by-products are plowed back to the ground for nutrient replenishment, but at worst they are left on the stubble or burned [3][4][5]. Considering the environmental impact, the last solution has the most harmful environmental effect because of the high degree of greenhouse gas (especially CO2) emission.

Utilization of agricultural by-products in building industry offers a good opportunity, as it can simultaneously provide a source of renewable raw materials and reduce greenhouse gas emission by incorporating the bound CO2 that was removed from the atmosphere by the living plant.

Unfortunately, very few research projects deal with the utilization of agricultural waste in Hungary, and the number of publications is limited. Apart from the use of some traditional technologies, very few innovative attempts were reported. This paper wants to emphasize that it would be desirable to draw more scientific attention in Hungary for the utilization of agricultural waste products in building construction because there is a significant source of raw materials.

II. AGRICULTURAL BY-PRODUCTS IN HUNGARY

The Earth's surface is 510 million km^2, from which 149 million km^2 (29%) is land and 361 million km^2 (71%) is ocean. 71% of the land (104 million km^2) is habitable, 10% (15 million km^2) is ice and 19% (28 million km^2) is barren land (desert, salt flat, exposed rock, beach). 51% of the habitable land (51 million km^2) is used by agriculture, 37% (39 million km^2) is forest, 11% (12 million km^2) is shrub and 1-1% (1,5-1,5 million km^2) is freshwater (river, lake) or urban and built-up land (settlement and infrastructure). From agricultural land 33% (17 million km^2) is cultivated, the other 67% is for livestock (grazing land) [6].

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In Hungary, because of its geographical location, the distribution of land use is quite different from the global situation. Topographical, soil and climatic conditions (great plains, nutrient-rich soil, high number of sunshine hours, ideal amounts of rainfall) of the country are extremely favorable for crop production. Consequently, the proportion of cultivated areas is much higher (57%). from which the vast majority (96%) is arable land. Among arable plants that have a relatively large crop production area, and a significant quantity of by-products are produced during its cultivation, the most important in Hungary are wheat, rye, corn, sunflower, rapeseed, sugar beet, potatoes, and peas [7]. Table I. shows that the majority of agricultural by-products is cornstalk, followed by cereal straws (wheat, barley), sunflower stalk, rapeseed straw, leafy beetroot, potatoes stalk and beans stalk [8]. Considering that a high proportion of cereal straw and leafy beetroot could be easily used for agricultural purposes (mainly for bedding and feeding), the annually arising amount of corn stalk, sunflower stalk and rapeseed straw waiting for utilization seems to be extremely significant.

In addition to arable crops, vineyards and orchards also occupy large areas in Hungary. As a result of their agricultural activity large amounts of pruned grape vines and fruit tree branches are produced, which are not used for anything other than incineration or composting.

TABLE I.

Plant	**Crop production area** *(ha)*	**By-product**		
		name	*tons/ha/year (average)*	*tons/year*
wheat	1 015 600	straw	6.2-8.2 (7.2)	7 312 320
barley	247 400	straw	6.2-11.3 (8.75)	2 164 750
corn	1 027 600	stalk and cob	6.2-14.8 (10.5)	10 789 800
sunflower	564 100	stalk	3.8-5.5 (4.6)	2 623 065
rapeseed	300 600	straw	3.2-9.5 (6.35)	1 908 810
sugar beet	14 100	leafy beetroot	30-56 (43)	606 300
potatoes	13 300	stalk	38-46 (42)	588 600
beans	15 200	stalk + root	5.2-11.4 (8.3)	126 160
fruit and grape	162 800	pruned branches	1.0-1.2 (1.1)	179 080

Consequently, it can be stated that a huge quantity of agricultural by-products is not utilized appropriately, because most farmers burn the stubbles after harvest due to the lack of any economical use of these materials. Stubble burning causes environmental damage, it reduces the soil fertility, destroys the nutritional flora and disturbs the natural balance. Moreover, it could lead to forest fires and soil erosion. The production of insulating material is a sustainable method from recycling agricultural by-products because it can prevent the environmental pollution and reduce energy consumption of buildings.

III. UTILIZATION METHODS AND POSSIBILITIES

In Hungary, except for a few examples of folk architecture, the use of agricultural by-products in construction has no tradition. Even among architects and manufacturers of modern building materials, we can hardly find a few, mostly isolated, attempts. However, the previous chapter highlighted the huge quantity of by-products generated year-by-year and the fact that the vast majority of them are not properly utilized. They are most often incinerated causing serious environmental pollution and greenhouse gas emission. To prevent or at least mitigate this, it would be necessary to utilize as many by-products as possible. In the following sections, the current utilization methods, the inherent potential of different by-products were investigated, and those international aspirations were chosen that could be adapted to the special conditions in Hungary.

A. *Cereal straw*

The utilization of cereal straw in the construction industry may have a significant history, although typically not primarily for thermal insulation purposes. Adobe made from a mixture of clay, earth and natural fiber (usually straw scraps) has been used worldwide for thousands of years [9]. In Hungarian folk architecture, straw was often used for roofing, where reeds were not available [10]. The construction of straw bales in the 1880s can also be considered a traditional method, even though the first straw house appeared in Europe only in the 1970s, and in Hungary only in 2002. The straw wall was initially built as a load-bearing structure, but later houses with walls made of wooden frames and straw bale filling appeared, where the straw already had a thermal insulating function [11] [12].

The first building board made of pressed straw was presented by P. Nicholl of England at the 1867 Paris World's Fair. Judd Cobb from the United States has also filed a patent for a similar product in 1871. The first pressed straw product suitable for construction was patented in 1923 by French engineer of Russian origin, Sergey Nikolayevich Tchaeff (1863-1944). He made chopped straw, which was compressed in a hydraulic press and connected them with galvanized steel wire [9]. It has been marketed under the name Solomit in many countries, including Hungary, and has been manufactured under this name in Australia since 1937 [10].

The first thermal insulation product made of straw was developed in 1935 by Theodor Wright Dieden (1889-1968) of Sweden. Under his patent, the first thermal insulation product made from pressed straw was marketed in 1945 with the name Stramit by Torsten Johannes Mosesson (1906-1974). Later, it spread worldwide as a frame-filling insulation [9].

In Hungary, under the name Shterra SSH100, 50x100 cm, 10 cm thick thermal insulation straw blankets (Fig. 1) have been manufactured with white linen (100 kg/m^3) and brown jute (90 kg/m^3) mounting, since 2020. The difference in volume density between the two products is due to the different degree of compression. To produce the panels, a special machine is used, which is able to automatically cut, compact and sew the straw. The straw is loaded into the machine on a tray, which is cut to size (if necessary) and then the material is sewn together with the mounting, which is compacted from the seam. The product's thermal conductivity is sufficiently low (0,039-0,041 W/mK) which close to the traditional thermal insulation materials (mineral wool, polystyrene foam). Its resistance against mechanical loads is relatively poor, its compressive strength is quite low (20-40 kPa), but its mechanical properties can be increased with plastering. It has good sound insulation quality and water vapor permeability.

The product can be plastered with lime or clay plaster in the traditional way, cement plaster should be avoided because it is harmful to the material. The plaster increases the mechanical resistance and stiffness, as well as protects the straw from decomposition, and moisture, as well as increases its fire resistance.

In terms of its environmental impact, it is a beneficial material, as the production does not require fossil energy sources, and no greenhouse gases are generated during it. Using local harvested straw, the transport energy is insignificant. As a demolition waste, it has no harmful effects on the environment. It can be plowed back to the ground and decomposed naturally, improving the nutrient content of the soil.

It is primarily suitable for thermal insulation, however, installation under high humidity (e.g., plinths) should be avoided. However, it is excellent for thermal insulation of facades and ceilings [13].

Fig. 1. Shterra thermal insulation straw blankets [13].

B. *Cornstalk*

The utilization of cornstalks is realized in minor quantities. Due to the late harvest, its nutrient content is low, making it less suitable for feeding. Due to its material composition and low calorific value, it is less suitable for biofuel production or combustion as biomass, which requires the production of pellets or briquettes. Because of all this, cornstalk is harvested in small quantities and the rest is either incinerated or plowed back, although the latter cannot be done unlimited because of the high potassium content of cornstalk.

Even though cornstalk is the largest agricultural by-product in Hungary, and a significant part of it is unutilized, its use in construction does not have the same tradition as that of cereal straw. In the folk architecture of Central and Eastern Europe, it rarely occurred that the outer surface of the walls of residential buildings (mainly adobe houses or wooden houses) has been covered with harvested cornstalks in winter to improve the thermal insulation capacity of the wall structure [14].

The first thermal insulation product made from cornstalks was made in the United States by Orland Russel Sweeney (1884-1958) and was marketed as Maizewood in 1929 for a shorter period [15]. In the 1950s, the American R. L. Lewis developed an insulation board that also included cornstalks. During its production, the cornstalks were treated with chemicals (e.g., insecticide), mounted onto plywood with a resin binder, and then covered with aluminum in order to improve the resistance against weather conditions and fire. However, due to the uneconomical production, its manufacturing stopped in the 1960s [16].

The Hungarian patent of 2009 for a thermal insulation block (Fig. 2) made of a mixture of synthetic resin and cornstalk can be considered a pioneering attempt [17]. During its preparation, the cornstalks were chopped, first mixed when dry then with its binder. The mixture was then filled into molds and pressed into blocks of different densities depending on the pressure applied and finally dried in the open air. The thermal conductivity of the blocks thus obtained varied from 0.045 to 0.055 W/mK as a function of volume density. In addition to its very good acoustic parameters, its strength properties have also proved to be adequate. Its dimensional stability and water absorption did not differ from other similar thermal insulation materials of natural origin (e.g., straw bales, wood wool). The tests were performed by the researchers of the Laboratory of Building Materials and Building Physics at Széchenyi István University (Győr, Hungary) between 2009-2013 [18] [19].

Unfortunately, production of the product has not started, and patent protection also expired in 2014. It would be important to revive and develop the technology because a large amount of raw material is available and the use of the product in construction could make a significant contribution to reducing the country's CO2 emissions.

Fig. 2. Cornstalk insulation block [17].

C. *Corn cob*

Corn cobs are available in much smaller quantities than cornstalks, and are preferred by farms, not as an environmentally friendly solution, to produce the heat energy needed to dry corn seed. Nevertheless, there are several examples of its use in construction.

The traditional *tabique* building technology (Alto Duro Region, Northeast Portugal) was developed in the 18-19th century. It consists of a regular timber frame structure filled and plastered with a mixture of raw earth, hydraulic lime and corn cob [20].

The first building insulation product was produced in Czechoslovakia after the World War II. It was a three-layer board with a corn cob core and a wood veneer face [21]. Later, in the 1970s Asian researchers raised the idea to turn corn cobs into insulating fiberboards [22]. They tested low volume density insulating boards made by using hot press method and using urea formaldehyde resin. The product had high mechanical strength and 0.096 W/mK thermal conductivity [23]. In 1986 Hungarian researchers also made a similar experimental product but the project was stopped, and the patent became forgotten [24].

In Portugal particleboards with different thickness and volume density were produced using milled corncob, wood glue and natural unmolding agent. Their thermal insulation quality was investigated, and thermal conductivity of these products was determined between 0.101-0.139 W/mK [25][26][27].

In Nigeria, researchers produced low density insulation boards from the mixture of sawdust, milled corncob and urea formaldehyde resin. Based on physical (volume density, water absorption, thickness swelling) and mechanical (flexural strength) experiments it was concluded that 50-50% sawdust and corncob content is the ideal [28].

Scientists from Cameroon made an attempt to use corn cob as pore forming agent in lightweight clay bricks. Different corn cob content was tested with various sintering temperatures, and it was found that corn cob content increased water absorption and decreased mechanical strength [29].

Based on the above, we can conclude that many alternatives to the construction use of corn cobs are being addressed in different corners of the world. To avoid the use of severely polluting utilization solutions such as incineration in Hungary, it would be important to pay attention to these attempts, as it have been seen above that there is a lot of potential in the use of corn cobs in building construction.

D. Sunflower stalk

The common uses of sunflower stalks are not much different from those of cornstalks. A small proportion (6-7%) of the resulting amount is harvested for feed or heat energy production, and its nutrient content and calorific value are relatively low. The vast majority of sunflower stalks produced in the fields are plowed back to the ground or burned. It is also used in a very small extent by other industries. Such is the case in the cosmetics industry, as some wrinkle creams contain sunflower stalk extract.

The first building construction product was a particleboard reported by American scientists in 1972. It was produced from sunflower stalk and aspen planer shavings, but the susceptibility to decay by fungi was hardly increased by the sunflower stalk content and the experiments were stopped [30].

In Turkey thermal insulation boards from different mixtures of textile waste, cotton waste and sunflower stalk was produced using urea-formaldehyde resin as bonding agent. Thermal conductivity of the products was measured to be 0.0728-0.1640 W/mK depending on the volume density [31].

French researchers also studied a bio-composite thermal insulation material made of milled sunflower stalk particles and 15% chitosan bonding agent. Volume density of the product samples was between 150-200 kg/m^3. The value of thermal conductivity was determined to be 0.056 W/mK, while compressive strength was 2.0 MPa and acoustic coefficient of absorption was 0.2 [31].

Also, a French researcher team manufactured thermal insulating boards from milled sunflower stalk using different kinds of natural bonding agents (starch, casein and bone glue made of gelatin) with various contents (10-15-20%). Thermal conductivity was determined between 0.0623-0.0823 W/mK depending on the type and the amount of bonding agent. Samples with bond glue had the lowest and samples made of casein had the highest value, in addition the highest bonding agent content caused higher thermal conductivity. Mechanical properties were inversely proportional to the thermal insulation ability [33].

It can be stated that despite the large amount of raw material available worldwide, only scientific experiments have been carried out for the utilization of sunflower stalks in building industry, and its practical utilization has not yet become widespread. After straw and corn stalks, sunflower stalks are the largest agricultural by-products in Hungary, and the utilization of the huge amount that is regenerated every year has not been resolved. Just for this reason, taking into account the experiments of previous researchers the production and marketing of a future building insulation product made from sunflower stalk has enormous potential.

E. Rapeseed straw

In 2003 the Directive 2003/30/EC of the European Parliament and of the Council promoted the use of biofuels in the European Union and it has set a target to replace 5.75% of all transport fossil fuels (petrol and diesel) with biofuels by 2010 [34]. This aim was repealed by the Directive 2009/28/EC to min. 10% [35] and the Directive 2018/2001/EC to 14% [36] in relation to the EU Climate & Energy Framework, which prescribed an overall 20% renewable energy use in the European Union by the year 2020 [37] and 32% by the year 2030 [38]. In Hungary the national target was also determined to be 14% by 2030. In order to reach this goal, the proportion of the first-generation biofuels (biofuels produced from crops and livestock) should reach min. 7% [39].

As a result, in many European countries (e.g., Germany, France) significant rapeseed production has taken place, and in some countries (e.g., Poland) the area of rapeseed fields has multiplied. This happened in Hungary as well. While in 2003 the area for rapeseed was only 71,000 hectares, in 2008 it was

246,800 hectares and in 2019 it was already 300,600 hectares. As rapeseed production is growing rapidly, the utilization of rapeseed straw as well as the rapeseed cake left over during rapeseed oil production has become an important issue.

There is currently no automated tool for collecting rapeseed straw, the harvester usually crushes and spreads it on the stubble. It is often burned causing environmental pollution [3]. Rapeseed straw is sometimes made into bales or pellets, which can also be used to make premium animal beddings; however, it is not a widespread form of utilization.

In Poland single-layer particleboards were produced from grinded rapeseed straw particles bonded together with a mixture of methylene-diphenyl-isocyanate (pMDI) and phenol-formaldehyde (PF) resins with 7:3 weight ratio. Physical and mechanical properties of these insulation boards were tested, and thermal conductivity was measured to be 0.065-0.080 W/mK depending on the volume density (450-650 kg/m^3) [40].

In France a special kind of lightweight bioconcrete was manufactured using crushed rapeseed straw and a mixture of hydrated lime (75%) hydraulic lime (15%) and pozzolan (10%) as bonding agent. Laboratory tests showed that thermal conductivity of this material was 0.125 W/mK, with a volume density of 539 kg/m^3.

A comparative analysis was carried out with hemp concrete, and it was found that both its thermal and mechanical properties are more advantageous (e.g., 2-3 times its compressive strength). Its impact on the environment has also been lower because it requires less binder, in addition to being not only easier to use as a raw material, but also easier to obtain and requires lower volume density to achieve the same material properties. In 2015, it was first used to renovate the facade of a rental building [41].

We can therefore conclude that there is no common practice for the use of rapeseed in construction, only a few scattered attempts are known. As rapeseed straw is available in significant quantities as agricultural waste in Hungary and there are no other uses, the utilization of rapeseed straw in the construction industry, like sunflower stalk and corn stalk, also has a huge potential.

F. Sugar beet residues (leafy beet end, sugarbeet slice)

The operational by-product of sugar beet cultivation is the leafy beet head, which is as valuable a feed for cattle as the beet slice, which is considered a by-product of the sugar production [3]. According to this, sugar beet residues are rarely used in other industrial sectors, nor can we find practical examples of their use in building construction.

Polish researchers have attempted to use beet slices and leafy beet head in construction. Three-layer particleboards were made, the inner layers of which were made of sugar beet residue, the outer layers of wood chips. The physical and mechanical parameters of the boards were examined such as volume density, water absorption, swelling under the influence of moisture, tensile and compressive strength, modulus of elasticity and screwability. The results showed that the high beet content has a negative effect on the material properties. However, particle boards with a beet content of up to 30% have already reached the minimum requirements for particle board, but only for indoor applications (e.g., furniture industry) [42].

French researchers used pellets and potato starch bonding agent after pulping, then extruding and drying sugar beet slices to make building elements with a volume density of 270-360 kg/m^3. Its thermal conductivity was 0.069-0.075 W/mK, and its water vapor diffusion coefficient was 8.9x10^{-12} kg/msPa. It has also been found that its sound insulation quality depends on relative humidity, porosity, and bonding agent content and that the best sound insulation can be achieved under normal laboratory conditions (23 °C, 50% relative humidity) with 10% binder content [43].

G. Other agricultural by-products

Due to the large amount generated annually, potato stalks, pea stalks, as well as pruned grape vines and fruit twigs are considered important agricultural by-products in Hungary.

In Hungary, potatoes grown in the fields are mostly harvested by machine, for which the stalk must be destroyed before harvesting. In the better case, the stalk stays on the stubble or is plowed back to the ground, in the worst case, the stubble is burned before harvesting, causing considerable environmental pollution [3] [44] [45].

Pea stalks, which are formed in much smaller quantities than potato stalks, are most often collected, as they are used for feed and excellent for green manure. As a result, only a relatively small amount is incinerated, however, due to its low calorific value and environmental impact, this solution is not preferred [3] [44] [45].

The large-scale occurrences of pruned grape vines and fruit twigs are different from other agricultural by-products, and the amount generated on vineyards and orchards is also significantly smaller. Cropped branches and twigs in the orchard, as well as most of the cut-off grape vines formed during the annual pruning of the vineyards, are usually burned outdoors. The smaller part of the pruned grape vines and fruit twigs, where the tools and methods are available, is crushed and mixed or plowed back into the soil. Due to the relatively high calorific value of twigs and grape vines, they can be burned; however, it requires special combustion equipments [3] [44] [45].

Unfortunately, there are no well-established attempts to use these agricultural by-products (potato stalk, pea stalks, pruned grape vines and fruit twigs) in building industry. However, the relatively large amount generated annually in Hungary justifies the investigation of possible utilization methods and experiments about the use of potato stalks, pea stalks, pruned grape vines and fruit twigs in building construction.

IV. Discussion

Based on the statistics of the agricultural sector, it is known that an extremely large quantity of agricultural by-products is produced in Hungary. The most significant types of these by-products are cereal straw, corn stalks, corn cobs, sunflower stalks, rapeseed straw, sugar beet residues (beet heads, beet slices), potato stalks, pea stalks, pruned grape vines and fruit twigs.

Of these, only cereal straw is harvested in relatively larger quantities, but even so, an extremely large amount remains unused. For the other by-products, the harvested rate is much lower. The most common way to deal with a significant amount of material that is not utilized in any other way is to incinerate it, which is highly polluting to the environment.

The utilization of agricultural by-products in the construction industry, apart from some insignificant amounts of cereal straw (e.g., clay, roofing), has no special tradition in Hungary. Commercially available building insulation products (pressed straw sheet, straw bale construction) are produced exclusively from cereal straw. In addition, only an attempt was made to create a construction product from cornstalks and corn cobs, but final product did not appear on the market.

Reviewing the special literature about the various innovative experiments according to this subject, it can be seen that research on the utilization of agricultural by-products is very active worldwide. It can also be stated that the primary goal of these product developments is to produce some kind of thermal insulation material.

V. Conclusions

Both the climatic conditions in Hungary and the regulations related to the design and construction of buildings make it necessary to make extensive use of thermal insulation materials. As a result, there is a demand for innovative materials, including thermal insulation materials made from various renewable resources.

It can be identifiable that most of by-products generated by agricultural activity are suitable (e.g., cereal straw) or may be suitable to produce thermal insulation material. From these by-products, the utilization of cereal straw, cornstalk, corn cob, sunflower stalk and rapeseed straw has the greatest potential in Hungary, because they are regenerated in large quantities year-by-year and the revealed special literature also reports numerous attempts about the utilization of them as a raw material of thermal insulation material production.

Although the use of potato stalks, pea stalks, pruned grape vines and fruit twigs as raw material of thermal insulation products has not yet been reported, it would be worthwhile to deal with it within the framework of a research project. This is justified by the relatively large amount regenerated every year and the current, especially polluting, utilization methods (e.g., incineration).

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