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ANALYSIS OF DIFFERENT PRE-TREATED PLANT MATERIALS FOR THEIR USABILITY AS INSULATION MATERIALS AND DIFFERENT APPLICATIONS

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Abstract:
Raw materials of annual plants fibres are not easily usable for industrial production applications. Pre-treatment of the annual plant fibres is necessary to increase the homogeneity of the material and to improve the material properties. This study deals with the influence of steam explosion treatment on the quality of annual plant fibres used as insulating material.
Wheat straw material was selected for production of insulating panels and bulk insulation material. To clarify the changes within the structure of the plants due to the pre-treatment process material analysis was carried out using FT-IR spectroscopy and light microscope.
The results showed that the pre-treatment process homogenizes the materials and the processes could be used for the production of bulk insulation and panels. A comparison of the results from other studies were done to show the potential of innovative materials and applications.

Key words*: thermal-hydro treatment of straw; thermal conductivity; wheat straw insulation.*

INTRODUCTION

Crops material used as insulating material has a long tradition. The applications of these natural raw materials need the considerations of the anisotropic material properties and microbiological issues as well as contamination from harvesting. Pre-treatments of these plant fibres have potential to decrease microbiological issues from the raw materials and increase their homogeneity and to improve the material properties (Nagl et al. 2015 a, b). In this study, the effect of steam explosion treatment of wheat straw material for insulating material was examined, and also based on the results an overview of the development of various materials and products for different applications are discussed.

The steam explosion treatment modifies the chemical composition, the sorption behaviour and the mechanical properties of wheat straw fibres (Han et al. 2009). A degradation of lignin and hemicellulose (polyose) was determined (Schnabel et al. 2019). The structural changes due to the steam explosion treatment were analysed by Han et al. (2010). They concluded that higher steam temperatures and longer retention times results in more homogeneous fibre materials. The analysis of thermal conductivity of miscanthus and maize straw materials shows that the steam explosion process has a positive influence. The treated and fractionated material with the same particle size range has lower thermal conductivity values than the raw materials (Schnabel et al. 2019). Moreover, the opportunity of glue less fibreboards made from

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steam exploded *Miscanthus sinensis* was analysed by Velásquez et al. (2002). It could be shown that the mechanical properties have increased due to the treatment process.

This study deals with the results of many different pre-treatment processes (e.g., mechanical, enzymatic or thermal-mechanical processes) of the raw materials of various plant species (Krenn et al. 2017a,b, Nagl et al. 2015a,b, Schnabel et al. 2019). Here the influence of the different treatment processes on the chemical, structural and technological changes of the material properties was analysed. Subsequently, the material was used for the production of insulating materials with natural adhesive systems on a laboratory scale, used to possible suitability of the treated raw materials for insulating materials.

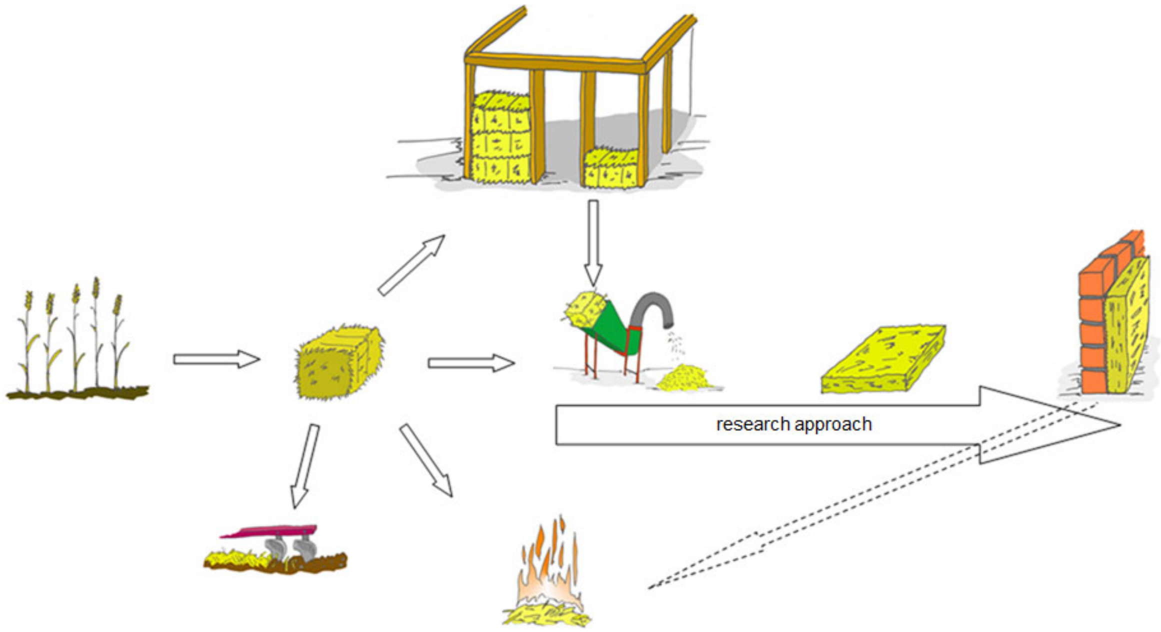

Fig. 1.
Research approach for the development of new insulation materials from different plant materials.

One possible opportunity to save raw materials (e.g., wood) and to substitute oil-based products is to use straw as thermal insulation materials (Nagl et al. 2015a). In Figure 1 is shown the research approach for the usage of unused raw straw materials from the agricultural areas. Straw as stating material is inexpensive, fast growing, locally available and easily manipulative. Normally, if the soil needs plant nutrient matter, then the straw materials are left/burned in the field. However, there are some agricultural fields that do not need the supply of additional substances. For this area the straw can used for other application. On the one hand the straw is also used for bedding of livestock breeding. On the other hand, this raw material can be used to develop innovative materials. The harvesting and production of the straw bale in the field is important for the further usability. Currently, straw bales are used either as load bearing structure or as infill wall (e.g., wood beam structures). Moreover, the increasing of the market shares of the bio-based insulation materials may yield a positive effect on long-term CO_2 fixation. This study shows potential of possible materials and products for insulating applications.

EXPERIMENTAL

Straw Materials

Straw of wheat (*Triticum L.*) was used for the analysis of insulating properties. The air-dried materials were mulched/chopped with agricultural equipment.

Steam Explosion Process

The straw was treated under steam explosion conditions using a pilot plant of the Upper Austria University of Applied Sciences. The pilot plant was detailed described by Eisenhuber et al. (2013). Steam temperature was 180°C and the retention time was 10 minutes. Each batch of about 900g of straw was put inside the steam chamber. The treated straw was dried to a moisture content between 6 and 12%.

Determination of the particle size distribution

The particle size distribution was analysed according to the DIN CEN/TS 15149-2 (2010). The vibratory sieve shaker AS 200 digit from Retsch was applied. For all materials the time for vibration was

15min with an amplitude of 50. The weight for each sieve was used to calculate the percentage of the different particle sizes.

FT-IR Spectroscopy

For the FT-IR measurements each raw material was milled with a cutting mill (Retsch) to pass a mesh of 500µm and the fractions between 250 and 63µm were separated with a sieving apparatus (Retsch). The spectra of the milled materials were recorded between 4000 and 600cm^{-1} with 32 scans at a resolution of 4cm^{-1} using a Frontier FT-IR spectrometer (PerkinElmer) equipped with a Miracle diamond ATR accessory with a 1.8mm round crystal surface. The average of three spectra was baseline-corrected and used for the further analysis.

RESULTS AND DISCUSSIONS

Steam explosion process is widely used for the pre-treatment of plant biomass (Schnabel et al. 2019). The performance of steam explosion process depends on temperature, retention time and particle size of the materials. For this study, the wheat straw biomass particle was put into a small vessel, pressurized and heated with steam 180°C temperature conditions and 10min processing time. After that the steam was quickly released and the straw particle exploded at atmospheric pressure into fibres due to a rupture of the biomass fibres rigid structure. The sudden pressure release of the wet particles defibrillates the cell complex of the lignocellulosic materials.

Fig. 2.
Raw materials of wheat with different treatments: a) chopped and b) steam pressurised at macro level, respectively as well as c) 2mm fraction of steam exploded and d) 500µm fraction of steam exploded material at micro level by analysing with a light microscope at 40x magnification, respectively.

Figure 2 shows the raw material of wheat before and after the steam explosion process at the macro and micro levels. The structure of the raw material is destroyed and it can be observed that this process frayed out the cell complex of the lignocellulosic materials. However, after the drying process some conglomerates of the materials could be seen for the wheat straw materials. The steam explosion influences on the material on fibre and fibrils levels were shown in Figure 2.

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pp. 24-31

The analysis at the macro level depicted that the particle size distributions between the natural and treated materials are different. The results from this pilot study showed that the size of the wheat straw particles tend to be smaller after the treatment than before the treatment (Figure 3). The portion of material fractions below 250µm were almost 3% for the chopped raw materials. By contrast the treated materials show an amount of 15%. The high difference about 13% between treated and untreated materials can be also observed in the next fraction between 250µm and 1mm.

Most of these fractions are dust and cannot be used for the development of insulating materials as well as this material is lost for the insulation material. However, this dust fraction has a high impact on the bulk density. The sieve results for the particle fraction larger than 4mm depict that the relative amount of chopped and steam treated wheat materials have as similar range of 44 to 39%.

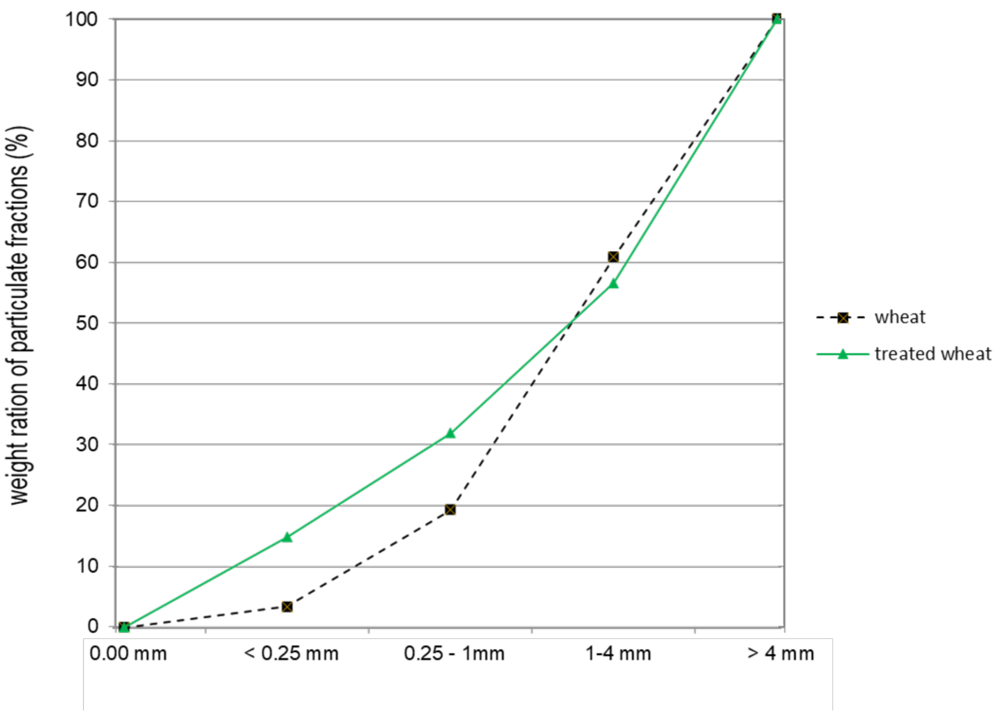

Fig. 3.
Particle size distribution regarding the raw wheat and treated wheat materials.

The chemical changes of the different materials due to the stream explosion process were analysed by using FT-IR spectroscopy (Figure 4). The chemical changes of the plant components due to the steam explosion occurred mainly in holocelluloses and in lignin (Schnabel et al. 2019). Also, an incomplete disruption of lignin-carbohydrate-complex happens, whereas the hemicelluloses are easily soluble and the pulp remains. This was also the first impression of the chemical changes caused by steamed pressurized treatments. A difference between the IR spectra of treated and untreated wheat straw samples were observed at the wavenumbers in the area about 2910cm^{-1}. The peaks obtained at 2930cm^{-1} and 2890cm^{-1} are an indication of stretching vibration form CH, CH_2 and CH_3 (Pretsch et al. 2010). These functional groups are corresponding with the wax on the raw materials. The peak at around 1730cm^{-1} is an initiation of carbonyl groups or COOH-groups, which may correspond with the hemicellulose. At around 1510cm^{-1} a peak can be observed, which are corresponding to the aromatic molecules (Pretsch et al. 2010). This peak can be increased due to the treatment based on the exploration process of the wheat straw materials. The band around 1240cm^{-1} was confirmed to the stretching vibration of C=O and COOH groups of aromatic compounds and hemicellulose. Based on this results, it can be assumed that the material composition was changed due to the steam explosion process.

Besides the chemical modification the material properties are important for the application for the use as insulating materials. Nagl et al. (2015a,b), Krenn et al. (2017a,b) und Schnabel et al. (2019) analysed the different material properties of various untreated and treated plant materials (e.g. from hemp, miscantus, maize). The use of steam pressurised materials has positive effects on the bulk densities and thermal conductivity by using fractionated materials for the insulation materials. Also, they stated that boards made

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pp. 24-31

out of untreated annual and perennial plants can keep up with conventional concerning the thermal conductivity.

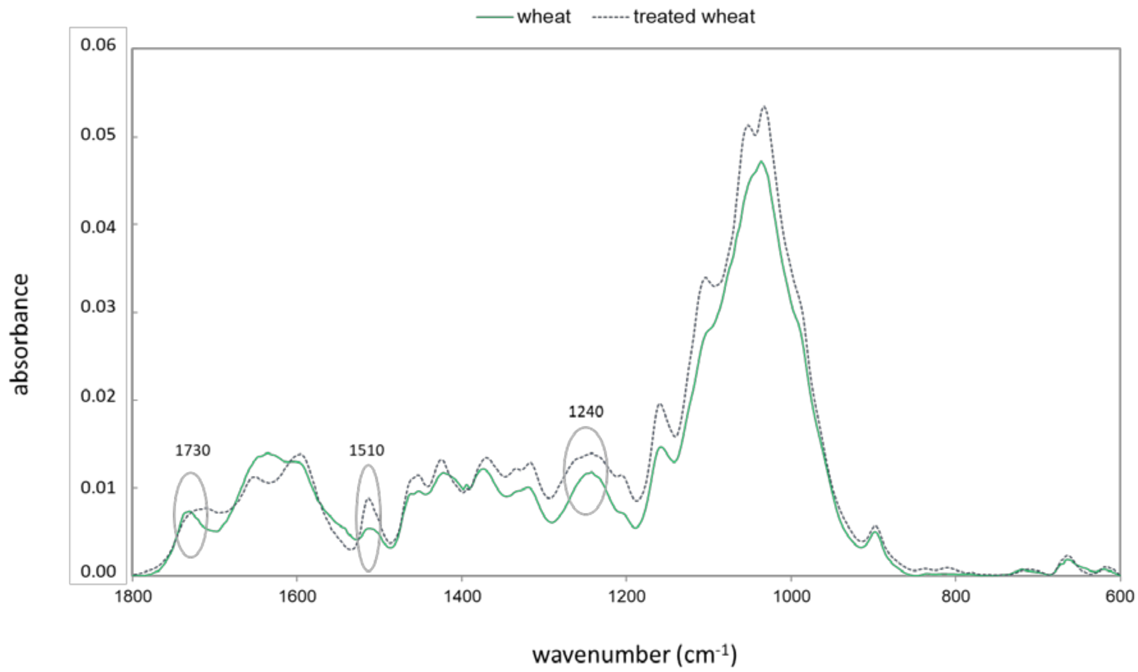

Fig. 4.
FT-IR spectra of treated and untreated wheat straw materials in the wavenumber range between 600 to 1800cm^{-1}.

Although mineral wool, polystyrene, PU and phenolic foam are able to achieve lower thermal conductivity the aspect of sustainability and the fact of economical and local acquirable recourse are good reasons for the use of plant materials for insulation materials.

Based on the results from previous studies by Nagl et al. (2015a,b), Krenn et al. (2017a,b) and Schnabel et al. (2019) different plant materials with various treatments were used to develop innovative products for insulating materials. This overview based on different treatments is shown in Figure 5.

As the treatment intensity increases, the digestion of the plant fibres or particles also increases the application possibilities of the material. For example, the straws with the lowest mechanical processing in the field cannot be used as fibre raw material for insulation boards or injection materials without further processing. However, it is also possible to use thermo-mechanically defibered material (e.g. steam explosion) for the production of fibreboard insulating materials. This study also showed, however, that the higher the treatment intensity of the material is the higher the fine fraction (e.g. dust) and the resulting material loss. In most cases, the fine fraction must be reduced by suitable methods in order to manufacture products or materials.

In general, straw can be used to manufacture a wide range of products and materials for the use of insulation materials. Current research suggests that straw can be used to insulate buildings.

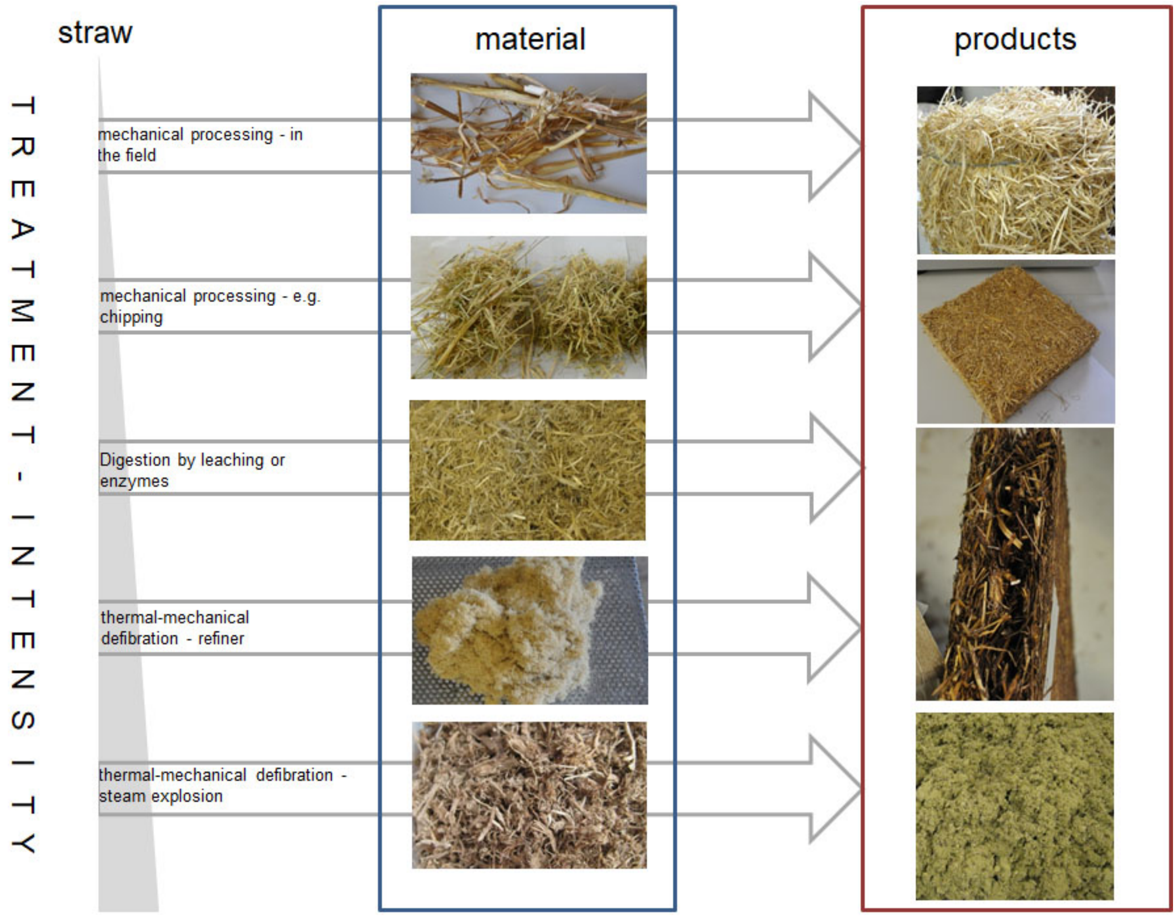

Fig. 5.
Overview of the starting raw materials and the resulting processed materials.

Different material properties can be achieved depending on the raw material (e.g. wheat and hemp), pre-treatment (e.g. chopped and steam pressurized), adhesive (e.g. tannin and water glass, ...) and bulk density of the boards (Nagl et al. 2015a,b, Krenn et al. 2017a,b, Schnabel et al. 2019). These influence the product concepts for outdoor or indoor use. Due to the achieved material strength, the boards can be fastened to the façade with commercially available screws and/or plugs for insulating materials (cf. Figure 6).

The first injection tests showed very good technological material values of the defibred straw with regard to density, thermal conductivity and injection behaviour. Therefore, the existing injection systems and wall structures can be used for the most part for the straw material. The raw density values achieved in the blow-in tests with the defibred straw showed comparable values as with cellulose or wood fibre blow-in insulation and should therefore also provide the necessary settlement safety. However, long-term investigations on the settlement safety of the material still had to be carried out. The individual material and product developments were evaluated with regard to the technical and economic areas and examined for industrial feasibility. The collection of the process data for the individual pre-treatments was carried out on the basis of the available literature.

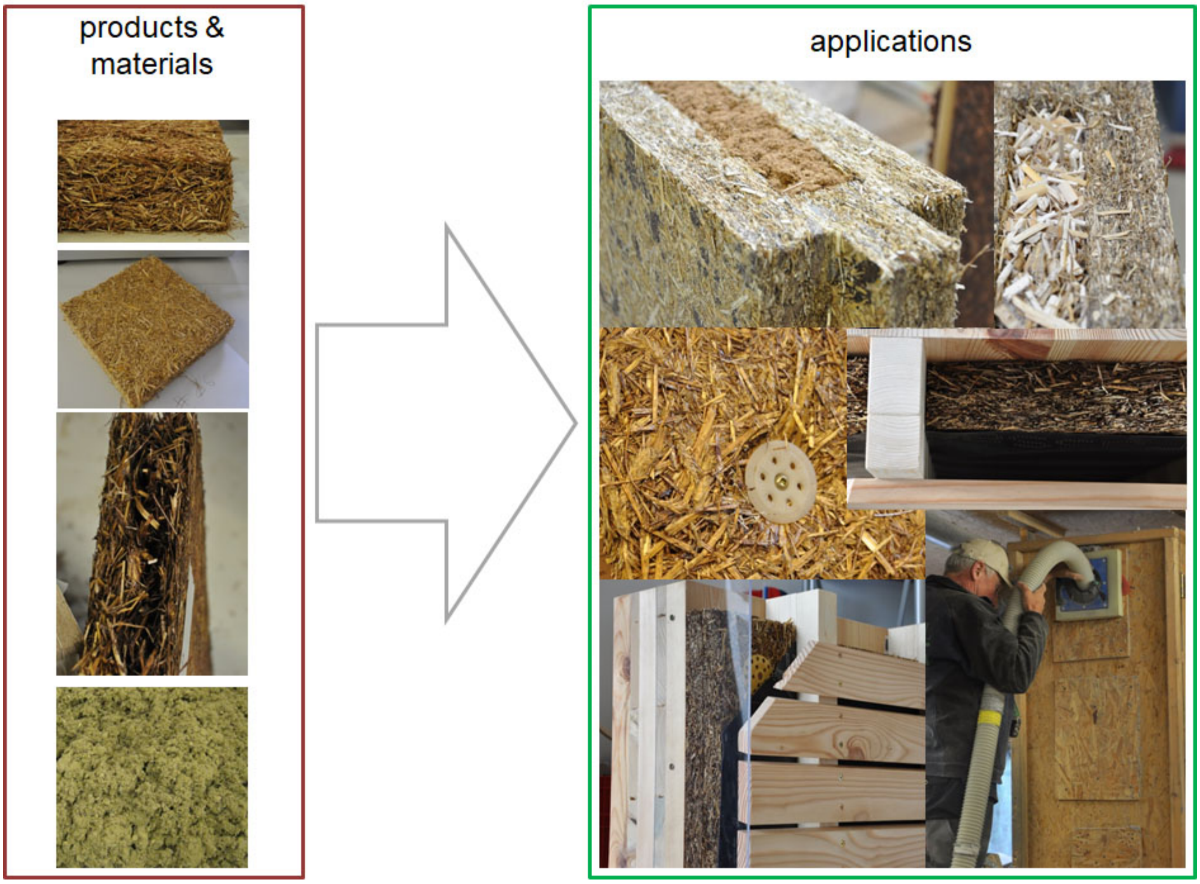

Fig. 6.
Overview of possible materials and products as well as their applications.

Since the pre-treatments in this study were carried out with laboratory equipment, these data are not representative and cannot be used for an objective consideration. Depending on the material pre-treatment, different insulating materials (e.g. board material or blow-in insulation) with different property values can be produced. Furthermore, natural adhesive systems (e.g. tannin, a natural ingredient from e.g. tree bark) with very good bonding properties were successfully used in the production of the insulating materials and thus include an important environmental aspect in the production and disposal of boards.

CONCLUSIONS

Steam explosion treatment were used to defibrillate the straw materials of wheat. These particles and fibres were analysed for the applicability as insulating material. Furthermore, based on this study and previous studies possible innovative products from the treated and untreated plant materials were outlined. Within the limitation of these results, the main conclusion can be drawn as follows:

- Boards made out of untreated annual and perennial plants can keep up with conventional concerning the thermal conductivity.
- The chemical composition of treated material is changing.
- The particle size of the steam pressurised samples decreases compared to the reference samples due to destroying of natural fibre composite.
- Lower material moisture contents were measured for the treated samples.
- The use of steam pressurised materials has positive effects on the bulk densities and thermal conductivity by using fractionated materials.

According to these results the possible application of natural and steam pressurised materials as bulk insulating material and insulating boards are shown. These findings provide a basis for help in transfer from laboratory to industrial conditions for consumer applications.

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