Insulation and Packaging with Natural Fibres: Contribution to the Smart City and Waste Reduction

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1 ABSTRACT

The current discussion in the literature on urban development raises the provocative question: are Smart Cities really sufficiently ecologically sustainable? Literature implies the need to re-define the Smart City concept in this context: A synthesis of the two terms 'Smart or Intelligent Cities' and 'Sustainable Cities as 'Sustainable Smart Cities' is suggested(Ahvenniemi et al. 2017). This paper agrees to put the synergy between the smart and intelligent ICT Smart city driven concept and the ecologically sustainable city framework higher on national and urban planning agendas. In this context, based on an experiment on 'Insulation and packaging with natural fibers', the authors of this paper suggest an innovative ecologically sustainable solution in the context of reducing plastic waste. The work aims to better establish natural materials in the technical foam sector, which is mainly dominated by plastic foams.The experiment is driven bynatural insulation materials instead of conventional materials such as EPS management with a potential high ecological impact for smart city ecosystems and corporate supply chains. The experiment,based on an innovative foaming process,strongly implies that it is possible to find ecological substitutes for current insulation and packaging materials that leave a significantly lower carbon footprint without compromising on quality. Suggestions for startup, ecosystem and marketing implications are provided.

Keywords: Smart City, Natural Fabrics, Insulation Material, Supply Chain, Marketing

2 INTRODUCTION

Amalgamizing the two terms "Smart or Intelligent Cities" and "Sustainable Cities," some authors (i.e. Ahvenniemi et al., 2017)propagate the term "Sustainable Smart Cities," shared by the authors of this paper.Albeit differing as to the content of the typologies of smart cities and sustainable cities compared to Ahvenniemi et al. (2017), Almeida, Guimarães, and Amorim (2024) confirm the emphasis on environmental protection in sustainable city frameworks and to the dubbing of the new term "Sustainable Smart Cities". The implicitly necessary higher public appreciation and intensified integration of protecting the Environment, Climate and Resources as well as highlighting respective objectives as national and community themes is suggested by Keppner et al. (2022) to the 'BUND' (Nation of Germany). In addition, and amongst others, latter authors call for an improved networking amongst all relevant stakeholders such as city administration, infrastructure companies, services or citizens in this context.

The careful and sustainable use of our finite resources is a central issue in solving climate and environmental problems. In globalized trade and also in digital retail, transport packaging is needed in large quantities for protection and/or insulation. Even today, packaging material is still largely made of plastics with an unfavorable CO_2 footprint and usually has an extremely short useful life. As a general rule, recycling is logistically far too costly. In Germany alone, 5.20 million tons of plastic waste are produced per year, and the amount of recycled waste is only 15.6% (Jeschke and Heupel 2022). Styrofoam is not considered economically recyclable.

A promising way to sustainably reduce the burden is to use raw materials provided by nature or from waste streams. Here, depending on the product concept, simple environmentally sound disposal can be made possible in addition to recycling. Depending on the intended use of the end material, different material properties come to the fore.

The focus of this work is therefore to develop an alternative to plastic foams based on natural materials. Depending on the use of the end material, different material properties come to the fore. The developments presented are intended to provide an alternative to expanded polystyrene, which is very popular in the packaging industry mainly due to its low thermal conductivity and low weight. Hence, the crucial product properties of thermal conductivity and density of the manufactured sample sheets are measured first and foremost. In addition, abrasion and material stability will be assessed. In the selection of the raw materials used, it is decisive that the material – as it accumulates – can be processed with the methods presented here without any further process steps.

Bénézet et al. (2012) describes the production and investigation of biodegradable foams to consist of 10 (w) % natural fibers. In his work, the starch foam matrix is the basic framework of the resulting material, and the natural fibers serve to improve the mechanical properties. The foams are produced by extrusion. Glenn and Orts (2001), on the other hand, produce starch foams using a compression-explosion process and investigate the properties of the foams. These also consist of a starch matrix.Bergeret and Benezet (2011) investigate starch and PLA foams produced by melt extrusion. Water and chemicals are used as blowing agents. Lopez-Gil et al. (2015) produce starch foams reinforced with natural fibers in three steps using extrusion, thermoforming and microwave foaming processes, where water acts as plasticizer and blowing agent. They make compostable foams using this process and investigate the mechanical properties. Kraus (2014)investigates microwave-induced expansion in extruded starch-based pellets from different points of view(Kraus, Enke, Gaukel et al., 2014; Kraus, Enke, Schuchmann et al., 2014; Kraus, Enke, Gaukel, et al., 2014).

The process presented in this paper is not yet known in literature. It focuses on the production of insulation materials with a high content of natural fibers or granules using natural binders in two steps, namely mixing or spraying and microwave drying or foaming. Compared to known processes, this procedure offers the significant advantage of using high proportions of residual or recycled materials. In this way, ecologically sustainable and fully compostable insulation materials can be produced cheaply and efficiently without the need for costly processing of the raw materials.

3 THE POTENTIAL IMPACT ON WASTE AND CO_2 REDUCTION

The authors aim to develop an ecologically sustainable solution with a potential high impact to increase cities' or regions' resilience and the wellbeing of their citizens. The reduction of waste plays a central role alongside ecologically sustainable construction. Packaging and insulation materials made from natural fibers offer decisive advantages here compared to conventional materials such as EPS (expanded polystyrene). The volume of 2.5 million tons of lightweight packaging waste per year in Germany (Volk et al. 2021) illustrates the great potential for recycling and avoiding waste and the importance of a functioning circular economy. The main components of lightweight packaging waste are polypropylene (PP), polyethylene (PE), polyvinyl chloride (PVC), polystyrene (PS) and expanded EPS. In contrast, insulation materials made from natural fibers, which can also be used as packaging material, offer a promising ecologically sustainable alternative. Natural foams can be made biodegradable and, therefore, contribute to reducing household waste. Their use also conserves resources and reduces the need for non-renewable raw materials. The potential ecological impact is illustrated in that the use of natural insulation materials such as recycled paper foam instead of EPS in a new urban development area with only 100 house roofs would lead to a reduction in CO_2 emissions of 1039 tons. This corresponds to a saving of over 80% compared to the use of EPS. This significant reduction portrays the positive influence of natural fiber insulation materials on the CO_2 balance in the construction industry and underlines their importance for sustainable urban development. In total, between 300,000 and 400,000 tons of EPS are used for house insulation in Germany every year (Report by the German Polystyrene Society). The production of EPS typically releases between 2.5 and 3.5 tons of CO_2 per ton of EPS. This means that in Germany alone, there is a potential CO_2 saving of 900,000 tons.

According to the International Polystyrene Society (PSI, year of publication; also include in references), around 5 to 6 million tons of polystyrene are produced worldwide every year, Insulation materials account for around 30 to 40% of total EPS production. Consequently, the production of the dominant insulation material EPS alone contributes to around 16 million tons of CO_2.

The hypothetical consideration can also be applied to the packaging industry:the use of 1,000 tons of expanded polystyrene (EPS) of a medium-sized logistics company in Germany for packaging every year, results in around 3,000 tons of CO_2 emissions per year. By switching to natural fiber foam, which has a 70-80% lower carbon footprint, emissions are reduced to 800 tons of CO_2 per year. This corresponds to a saving of 2,200 tons of CO_2 per year – comparable to the CO_2 absorption of 176,000 trees per year (cf. "Dena-

Leitstudie Aufbruch Klimaneutralität" 2021). By their citizens using such materials, cities can actively contribute to climate protection and significantly reduce their environmental impact.

4 THE CURRENT TECHNICAL STATE OF THE ART

As the construction and infrastructure sector accounts for 35% of energy consumption, 35% of emissions, 50% of resource extraction and over 50% of total waste generation, a shift to a circular economy that minimizes the use of raw materials and maximizes recycling processes is urgently needed to reduce environmental impacts in the long term (Berger, Prasser, and Reinke 2013).

Although numerous processes exist to produce technical foams from plant-based raw materials, the end products are often classified as plastics. For example, bio-based polyethylene (bio-PE), which is made from renewable raw materials such as sugar cane, is chemically identical to petroleum-based polyethylene and is therefore not biodegradable (Thielen 2020). Another example is the development of lignin foams. The Fraunhofer Institute for Wood Research (WKI) is working on the production of foams from lignin sulphonate, a by-product of pulp and paper production. Although lignin is a bio-based raw material, this does not automatically mean that the foams produced from it are biodegradable. The decisive difference in the present work, therefore, lies in whether a bio-based plastic consists only of renewable raw materials or whether it is also biodegradable. In practice, this means that not every "bio-based plastic" is automatically more environmentally friendly – especially if it behaves in a similar way to fossil-based plastics at the end of its life.

Fortunately, the use of natural fibers in insulation materials and packaging has made considerable progress in recent years and is gaining increasing acceptance both technologically and in terms of ecological sustainability. In both areas, dry wet and molded fiber processes are used.

Natural fiber-based insulating materials such as hemp, flax, wood fibers and cellulose are increasingly in demand due to their environmentally friendly properties and good insulating performance. They offer advantages such as high moisture regulation, good sound insulation properties and a positive ecological balance. In addition, they are often less energy-intensive to produce and can be disposed of or recycled more easily at the end of their life cycle. The Fachagentur Nachwachsende Rohstoffe e.V. (FNR) has published a comprehensive market overview of insulation materials made from renewable raw materials, which provides detailed information on various materials and their applications(Fachagentur Nachwachsende Rohstoffe e. V. (FNR), 2020).

Natural fiber-based materials are also becoming increasingly important in the packaging sector. In addition to the traditional processes for producing paper and cardboard from cellulose fibers, packaging made from numerous types of natural fibers is already being produced using innovative methods such as thermoforming and dry forming.

In the present work, various natural fibers and binders are combined to form a material structure. The aim here is to offer a natural alternative to expanded polystyrene that can be produced with little effort. Two different approaches are used for production, whereby foamed or cross-linked fiber networks are created via individual points. Both methods used here utilize the microwave drying process. Waste paper, straw, hemp, wood shavings, seaweed, cork and tree bark are used as the material matrix, while starch and methyl cellulose serve as binders and sodium hydrogen carbonate as a blowing agent.

5 THE EXPERIMENTAL METHOD

5.1 Materials

Waste paper, starch and methyl cellulose used in this work are considered chemically converted raw materials, while hemp and wood chips are physically converted; straw and seaweed can be categorized as raw (untreated) raw materials.

Starch and methyl cellulose are used as hydrocolloid binders. Starch is a polysaccharide and exists as a mixture of unbranched amylose and branched amylopectin. The amylose-amylopectin ratio depends on the plant species. The size and shape of the starch grain vary depending on the plant. The rice starch used in this work has a grain size of 4-5 µm (Behr and Seidensticker, 2018; Trueb 2020).Methyl cellulose is a cellulose derivative that forms a gel with water. The material is used as a thickener and binder.

5.2 Formulation

In formulation, fibers, binders and possibly blowing agents are mixed with pre-tested proportions puruing two different approaches. One is a formulation for foaming and the other is used for cross-linking the fibers. The proportions in the dry material for these different approaches are listed in Table 1.

	Averaged mass fractions foaming %	Averaged mass fractions at cross-linking %.
Fiber	85	85
Binders	10 (Methyl cellulose)	15 (starch suspension w/w)
Blowing agent	5	-

Table 1: Proportions of fiber, binder and blowing agent in dry matter

The required water amount was determined in preliminary tests based on fiber type and production method. For foaming, optimal viscosity ensures maximum volume expansion, with an average water content of 200% (dry mass). In fiber cross-linking, water content is reduced to 120% to maintain sprayability while minimizing excess moisture.

Foaming with sodium bicarbonate, binding with Methyl cellulose

The fibers are mixed – as indicated in Table 1 – and water is added. Mixing produces a paste-like mass. The mass is dried in the microwave in a homemade Teflon mould with the dimensions 16 cm x16 cm x 4 cm.

Spraying with starch suspension

A 15 % (w/w) starch suspension is sprayed onto the fibers during the mixing process. The fibers are then dried in the Teflon mould in the microwave.

6 ANALYSIS

Microscopy

The microscopic images were created with a Keyence VHX-700 3D microscope.

Thermal conductivity

Thermal conductivity is measured using a guarded hot plate apparatus. The temperature gradient applied to the samples is maintained by means of a hot plate. The thermal conductivity of the material can be calculated via the heating power required for this(Sonnick et al. 2019). The SRM 1453 (Expanded Polystyrene Board) from NIST (National Institute of Standards and Technology) serves as a reference for all measurements (Zarr and Pintar 2012)

Density

The density of the material is determined by the dimensions and weighing.

Three-point bending test

For specimen preparation, reference points are taken from the standards DIN EN ISO 14125 (Deutsches Institut Für Normung. Faserverstärkte Kunststoffe – Bestimmung Der Biegeeigenschaften (14125)) and DIN 51902 (Bestimmung Der Biegefestigkeit Nach Dem Dreipunkt-Verfahren – Feststoffe (51902)). The testing machine complies with the requirements of DIN EN ISO 7500-1.

7 RESULTS AND DISCUSSION

In the following, the samples produced and the important key points in the entire process are described quantitatively, and the results of the microscopic examinations, thermal conductivity and density measurements as well as the three-point bending tests are presented.

Qualitative assessment

In addition to the haptic description, the qualitative description of the manufactured samples includes the naming of the most important points in the processing of the starting materials. The following statements also encompass knowledge from preliminary investigations. In general, it should be noted that the finer the fibers are ground, the lower the density of the samples produced. The fiber length plays a major role in fiber cross-linking. The longer the fibers, the more elastic the resulting sample. The samples produced show different abrasion behaviors. The sample with cork and bark is most prone to abrasion, followed by wood foam, seaweed, hemp, straw and finally waste paper (see figure 1). Waste paper haptically resembles pulp and shows hardly any abrasion. The foamed samples show clear shrinkage behavior, whereas this is not the case with cross-linked fibers. Different levels of thickness can be produced with all samples.

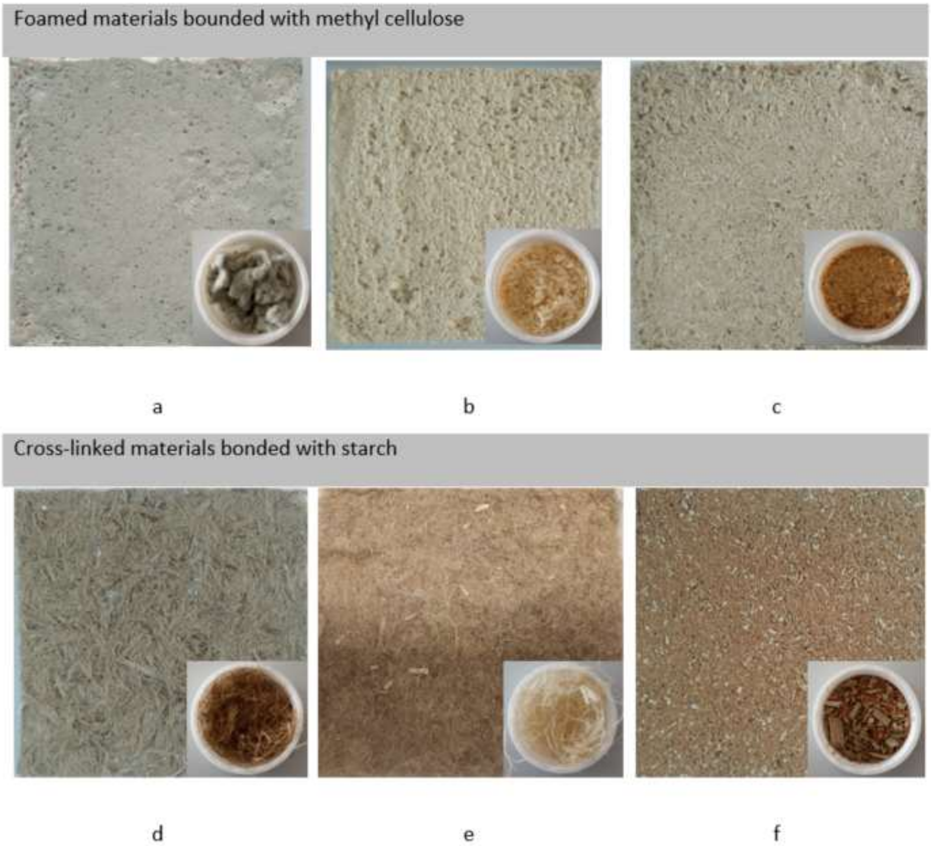

Figure 1. Samples: a: wastepaper; b: wood shavings, c: straw; d: seaweed; e: hemp; f: cork bark

Microscopy

The starch adhesive is observed as a cross-linking point in many samples and appears as a shiny transparent layer (best seen in Figure 2 h and l). The cross-linking points are irregularly distributed over the sample surface. While some of them are connected by long arms, others are present as isolated points. The adhesive is visible to the naked eye as a transparent layer. Microscopy shows that the adhesive layer has many interruptions and is dotted with pores of different sizes (cf. Figure 2 e, f, g, h, k, l). Among the foamed samples, the waste paper sample has the finest structure compared to the cork bark sample and the wood chip sample. The cork bark samples have the coarsest structure and, as granules, have the most irregular surface structure. The coarser the material, the deeper the pores that are visible to the naked eye. The material's own porosity and hygroscopicity probably also plays an important role in the distribution and absorption of the adhesive. In the cork bark sample, the individual granules are almost completely covered with the adhesive, while in the seagrass sample individual cross-linking points can be observed. In the hemp samples, neither cross-linking points nor a glue view are visible.

Thermal conductivity, density and mechanical stability

For this investigation, plates are produced in a Teflon mould with dimensions 16 cm x 16 cm using the formulations and production methods from 5.2. The thermal conductivity of the samples is determined at atmospheric pressure at an average temperature of 30 °C (hot plate 45 °C, cold plate 15 °C). The measurement is carried out with a guarded hot plate apparatus; the more precise specificationscan be taken from Sonnick et al. (2019). The volume is determined by multiple measurements of length, width and height (thickness) along the edges of the material. The weighing is carried out three times per sample. The density is calculated via the average values. The results of the three-point bending test are given in Table 2 based on the maximum force at break related to the material thickness with the standard deviation. In addition, the averaged thermal conductivities, densities and material thicknesses are listed in Table 2.

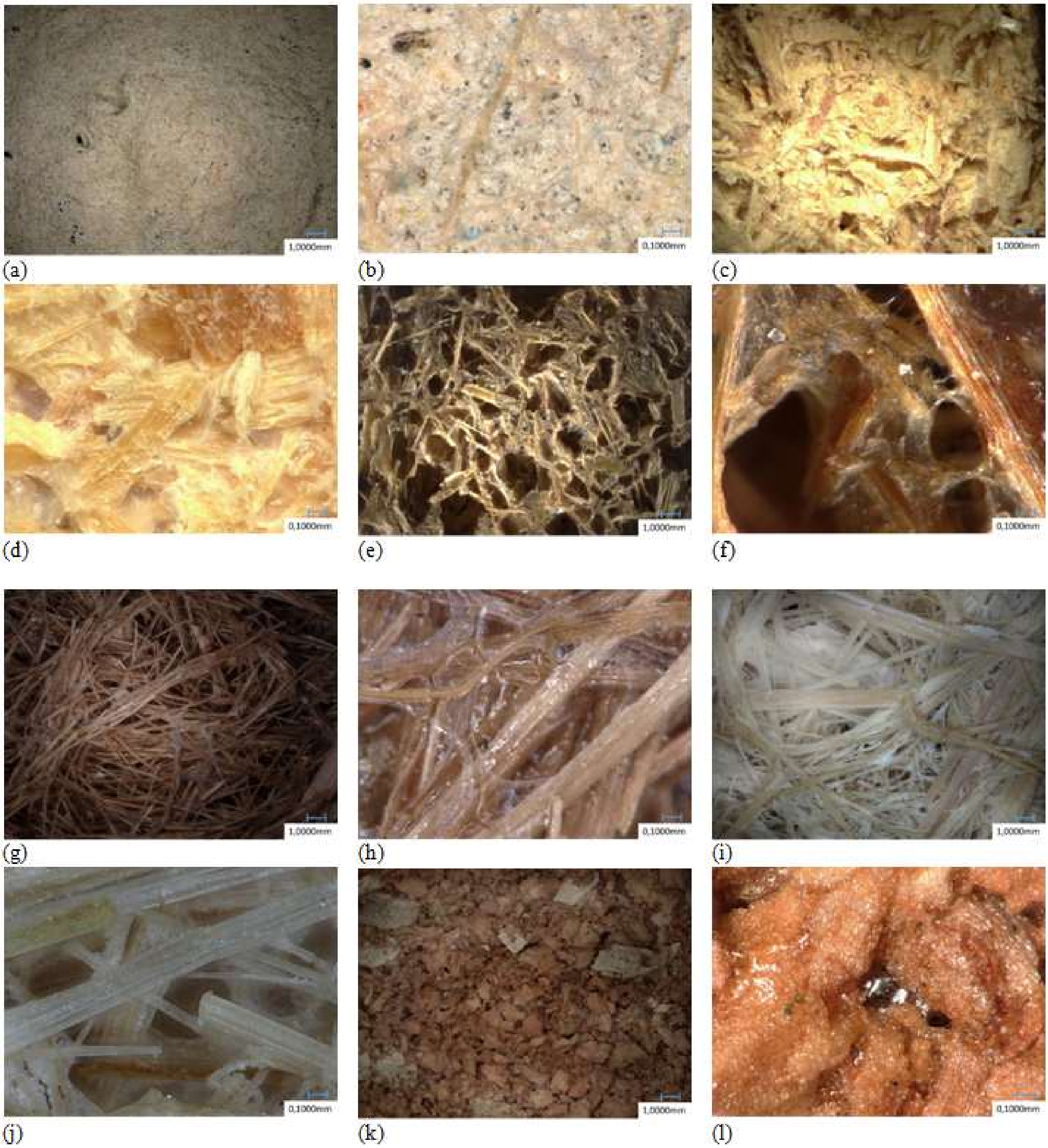

Figure 2. Microscopic images at 20x (left) and 100x (right) magnification with Keyence digital microscope. (a), (b): wastepaper; (c), (d): wood shavings, (e), (f): straw, (g), (h): seaweed, (i), (j): hemp, (k), (l): cork bark

Sample	Thermal conductivity	Density	Breaking stress	Standard deviation breaking stress
	mW/mK	kg/m³	MPa	MPa
Polystyrol (EPS)	37	43,2	0,82	0,02
Waste paper	36	105,3	0,16	0,06
Wood shavings	47	156,3	0,18	0,03
Straw fine	37	112,6	0,40	0,04
Seaweed	43	145,6	0,17	0,03
Hemp	51	105,6	0,74	0,20
Cork + bark	42	166,2	0,39	0,10

Table 2: Thermal conductivities, densities and mechanical stability of the manufactured samples.

EPS, which serves as a reference material here, is a very light material with low thermal conductivity and low density. The material properties are, as already mentioned, optimal for use as insulation and packaging material. The material shows hardly any abrasion, is dimensionally stable and has a homogeneous pore structure. The measured thermal conductivity of 37 mW/mK and the density of 43.2 kg/m³ (Table 2) confirm the previous statements on the suitability of the material as packaging and insulation material. By means of the maximum force leading to breakage, the breaking stress is calculated and given in Table 2. The stress value includes the geometric influences, e.g., the material thickness and, thus, the material consumption. At this level, the highest degree of material stability can be determined for EPS. None of the samples can reach the low density of EPS. The lowest density of 105.3 kg/m³ is achieved by the wastepaper sample. The hemp fiber sample follows with 105.6 kg/m³. The coarse-grained cork bark sample has the highest density of 166.2 kg/m³. The wastepaper sample has the lowest thermal conductivity of 36 mW/mK, and the straw sample also has low thermal conductivity of 37 mW/mK. Wastepaper and straw samples also perform best in the three-point bending test.

The results showthat it is possible to produce boards from natural fibers or granulates and natural binders by means of microwave drying. The samples from wastepaper and straw come closest to the reference material EPS in terms of thermal conductivity, density and abrasion. The somewhat higher densities of the new insulation materials do not necessarily have to be seen as a disadvantage, since in the shipping industry in particular one is basically dealing with transient heat transfer processes. Here, it is not thermal conductivity but the thermal diffusivity that is decisive. Due to the resulting inclusion of a storage term, materials with a higher density and the same thermal conductivity even perform better in this comparison. The advantage of being able to produce the panels at low cost without having to process the raw materials should also be emphasized again at this point. Costly processes such as extrusion can be bypassed. The high water content in the two proposed formulations must be removed during microwave drying. There is a need for optimization here. For both the optimization of the foam properties for insulation purposes, as well as for the energetic optimization, optimal fiber-binder-blowing agent-water proportions can be developed in further work through parameter studies.

Implications for a startup ecosystem and marketing

Once the aforementioned still pending optimization processes are completed, the commercialization and roll-out of the research comes to the fore. After the patent has been assured, the research is suggested to be marketed by startups due to their higher ability to test the marketand higher level of flexibility for innovation.Later, for the end of the life cycle, for scaling purposes, co-operation with or acquisition by big companies can be envisioned. At the birth stage of the startup, a Minimum Viable Product (MVP) must be developed. According to Tripathi et al. (2019), supporting startups to find the fundamental problem-solution fit and to facilitate the learning process during the MVP process, improves their chances to successfully manage and survive the MVP stage within the difficult first two years. In this context, the previous authors suggest a supportive startup ecosystem being in line with the authors of this papers. In the following, some possible supportive activities of respective startup ecosystem stakeholders are schematized (see Westphal et al. (2022) for an applied best case example of the ecosystem of the city of Mannheim)). First of all, a strong ecologically sustainable engagement of the city/region reflected, for example, by a commitment to the smart city movement in general and to the climate neutrality in particularprovides a fertile ground.Furthermore, the resources of a network of experienced representatives of successful local companies might be approached to support in the production of the 'physical product' such as plates or packaging material. To approach potential entrepreneurs, university spin-offs transferring their invention to graduates or private local companies, might be a viable option. In addition, graduates from undergraduate or postgraduate university courses, or information, networking and educational eventsby local universities, incubation centres or accelerators, city departments/joint ventures or entrepreneurship associations(especially also female ones) and/or business angelsarepromising routes for recruiting entrepreneurs. Very important is the initial educational support of startups and their human capitalin terms of technology applied (in this case, for example, biodegradable natural fabrics application and knowledge on material properties) and entrepreneurial education; latter refers, for example, to sustainable business development and startup/entrepreneurial competences provided, for example, by universities and/or consultants. Including the future market, in this case the citizens, construction, packaging or logistics companies, architects, as well as city representatives (especially in the case of the existence of city quarters to be energetically and ecologically redesigned) in co-creating the problem-solution-fit is suggested.Later, achieving a market-product fit and quickly implementing and continuously reflecting and improving on the suggestions of the co-creators is regarded another key success factor. Paramount is, of course, the support in terms of financial resources, i.e. from business angels and venture capitalists for seed and growth capital, city departments, banks, accelerators, philanthropistsor via crowdfunding. After having successfully found a market-product fit, further mentoring and educational support is proposedto find a best channel-product and communication fit. As, after this stage, increased growth resources are required, the development of a detailed sustainable business model, including, for example, concepts such as networking, value proposition canvas, sustainable value mapping (Bocken, 2021) or sustainable supply chain are suggested, to convince potential investors at this stage.Regarding the latter, the minimum possible transport distances seem a given, simply because most of the raw materials are usually available in the region, in turn leading to enhanced support for the local economy. Moreover, the faster local access to raw materials is, the more efficient and sustainable the supply chain planning will be: this is supported by corresponding certifications of these available raw materials, i.e. FSC for wood. As fewer other additives are required when processing natural insulation materials, regardless of whether these are chemical or synthetic in nature, a further reduction in the entire supply chain, and, importantly, a health benefit might occur. It is obvious that increased CO_2 neutrality or biodegradability will have a lasting influence on corporate communication and, hence, an effective sustainable marketing or business model impact (Bocken, 2021). Storytelling in the channel-product-fit stage on innovative natural materials, i.e. via social media, might strike a balance to the often prevalent perception of the building materials industry as an ‘energy waster’.

In order to establish the optimal marketing of sustainable insulation materials made from natural materials, the choice of which material can best be marketed, where must also take a geographical component into account. Regional differences and their raw material deposits are highly diverse. Thus, it does not make much sense, even ecologically, to use insulation materials made from seaweed in regions thousands of kilometers away from coasts with access to the sea.

We also see that the use of different raw materials has a strong influence on the entire marketing of the respective products, sales markets, distribution channels and much more.

Recycled paperas insulation material is illustrated in the following, geographically the least critical, case (Naturanum, n.d.; Koala Insulation, n.d)

Recovered paper as a raw material for insulation material is sustainable, cost-effective and in high demand in the construction industry. It can be processed into cellulose insulation (blow-in insulation, mats) or innovative composite materials. Here are two of the possible business models that could be considered:

(1) Licensing to building materials manufacturers, through recycling companies that work directly with insulation manufacturers. The advantages here are obvious, with the development of an innovative and smart insulation technology (cellulose-based) from recycled paper. Further advantages of this form of technology sales are the very fast market access via existing and well-established companies, as well as the zero production costs, which also leads to very fast and high scalability. The sales challenges on the other hand are manageable and are only referring to the investment for material development, and to the dependence on the possible licensees, who are ultimately responsible for the sales success.

(2) Engaging in high-tech construction projects such as eco-friendly buildings in the luxury and high-end sector, based on high-performance cellulose insulation with a technical add-on, such as a hydrophobic coating, to ensure increased protection against moisture. Likewise, with the appropriate coating, one can argue much better on the subject of fire protection, especially with the raw material “cellulose”. Another component could be an additional coating with “aerogel” insulating materials to make the good insulation values even more efficient, in order to achieve a far better market positioning as a so-called premium building material. This in turn leads to the marketer, be it, for example, the high-quality building materials dealer with significantly higher yields and also less local competition, carrying out more attractive marketing through the premium positioning. This is now also becoming an increasingly important topic for property developers an architects with regard to sustainable construction projects. The challenges associated with this lie here again in the extensive and costly material development and the necessary certifications/ standards for the market-ready product, which requires a high investment budget and certainly correspondingly higher marketing funds.

Contrarily, the example of seaweed as an insulating material is juxtaposed: geographically highly critical, since only certain regions worldwide are suitable (Building Centre, 2017).

Seaweed as a raw material for insulation material is both sustainable and innovative, although the sustainable extraction of seaweed as an insulating material is certainly more difficult than with other natural materials. Here, too, two possible business models demonstrate the diversity of marketing:

1.To somewhat counteract the geographical restriction in this case, the first concept would be quite suitable. In this case, long-term co-operation with agricultural and/or aqua-farm operators would serve as a source of raw materials, because local independence is a given here; in the case of both "raw material producers" such as agricultural operations or aqua-farm operators, proximity to the lake is not absolutely necessary. With aqua-farms, sustainable raw material production can take place with special aquacultures. Further marketing remains in the hands of the "producers" and can be sold directly to the processing company. Thus, very low production and manufacturing costs go hand in hand with the greatest possible support measures, e.g. from environmental organizations. Short distances from production to final use are thus ensured and do their part to reduce the carbon footprint. The positive aspects in this distribution model are counterbalanced by only a few, albeit important and sometimes difficult to calculate factors. These include the certainly fluctuating harvest volumes influenced by environmental factors, as well as a seasonal challenge, which goes hand in hand with strong dependencies and few flexible options with regard to production partners and ultimately also distribution partners in the long term.

2.A business model in which the recycling approach can be implemented quite well, in addition to the use of the natural material as an insulating material, is, in principle, also referred to here as the cradle-to-cradle model (Streich and Hartje, n.y). Here, the development and production of fully biodegradable seaweed would come first, in order to pursue the approach mentioned from the ground up. This would be accompanied by the development of an efficient take-back and recycling process for these insulation materials, which would add immense value to a circular economy in the positive argumentation. A clear differentiation from classic and sustainably produced insulation materials underlines the sustainable marketing model. This requires specialized building materials dealers who can also provide well-founded advice. In addition to funding from environmental funds, for example, or investors from the environmental, social or ESG sectors, there is another exciting approach to marketing to the end consumer, namely selling CO_2 certificates, to name another possible source of income. The longer time to market for such a model is certainly more of a challenge at present, due to the need to set up and implementproduction and take-back processes, which will balance out in the long run.

Market development

To provide a better overview of the rapid and positive global development and the overall market potential, we have zoomed inglobal economic forecasts on some aforementioned examples of natural materials (. The market for sustainable insulation materials made from natural materials will grow significantly in the next 10 years. This is driven by stricter environmental regulations, rising energy prices, growing awareness of CO_2 reduction in the construction industry and technological advances.

- The global market for sustainable insulation materials is expected to grow from USD 15–18 billion (2024) to over USD 30–40 billion (2034) (GMI, 2024)
- This corresponds to a compound annual growth rate (CAGR) of 6–9 %.
- Natural insulation materials (e.g. hemp, wood fiber, cellulose, sheep's wool, seaweed, straw) could increase their market share from the current 5–8% to up to 15–20%.

Insulation material market development (2024–2034) in more detail (FairWell, n.d)

Hemp:Very strong growth due to improved availability and correspondingly lower costs of approx. 6–8 %

Wood fiber: Well established, and will continue to grow steadily and solidly at approx. 8–12 %

Cellulose: Inexpensive raw material & efficient, high growth expected at approx. 10–15 %

Straw: can be easily integrated into the circular economy, but is associated with scaling problems approx. 2–5 % growth

Seaweed: highly innovative natural material, an absolute niche with great future potential, currently at approx. 1–3 % growth.

We therefore see three major growth markets worldwide (FNR, 2019; GVE, n.d)

The EU as the leading market for natural insulation materials, with the strongest growth due to stricter environmental laws such as the EU taxonomy or the so-called Green Deal Initiative. Countries such as Germany, France, Scandinavia or the Netherlands are playing the absolute pioneering role here, which, due to the high demand for CO_2-neutral insulation materials, significantly increases the market opportunities for wood fibers, cellulose and seaweed Materials.

The USA shows a growing demand but also faces challenges still remaining on the acceptance side. It is now being presented to a wider audience through standards in the green building sector or through energy efficiency programs. Hemp and cellulose have the greatest potential here, while seaweed is currently still considered a niche product.Which is actually not quite understandable, since the US has a relatively long and geographically extensive coastline.

The third growth market is the People's Republic of China, with a huge market potential at the start of the development. However, the first major pilot projects have already been launched that recognize the place of hemp and cellulose as insulation materials in sustainable urban development. With its rather long coastal regions, seaweed as another natural material that could quickly increase in acceptance.

In terms of their use as insulation materials, the naturall materials we have discussed are indispensable, and the same applies to other applications and rapidly growing markets. In addition to medical and chemical products, the most demanded product groups are temperature-sensitive products such as food and beverages and the requirements of their"cold chain" during the storage and transportation of these temperature-sensitive product groups. This also requires refrigerators and freezers, as well as the trucks, railway carriage or airfreight containers in which the insulating materials made of natural materials are also finding their way in.

Based on this paper, there are also two fundamental directions in the construction industry that offer immense market opportunities. However, these need to be differentiated as to basic marketing. Classic residential construction, which also includes the entire spectrum of renovation, and the construction industry for commercial use of factory buildings or halls. In the broadest sense, this can also include warehouses and, for example, greenhouses, whether in industry or agriculture, all of which require temperature sensitivity as a must in planning, construction and operation over decades as a common thread.

8 CONCLUSIONS

The development of the sample materials of the experiment provided shows that it is possible to find ecological substitutes for current insulation materials that leave a significantly lower carbon footprint without compromising on quality. The materials presented can also be produced and applied decentral in third world countries without the need to build huge factories. The findings imply that the samples from waste paper and straw come closest to the reference material EPS in terms of thermal conductivity, density and abrasion. The findings of this research in progress suggest scope for optimization. For both, the optimization of the foam properties for insulation purposes, as well as for the energetic optimization, optimal fiber-binder-blowing agent-water proportions can be developed in further work through parameter studies. Once this optimization steps are finalized, however, commercial success – based on successful startup life cycle design and sustainable business modelling- can be envisaged due to the high potential impact of the innovative product on waste and CO_2 reduction.

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