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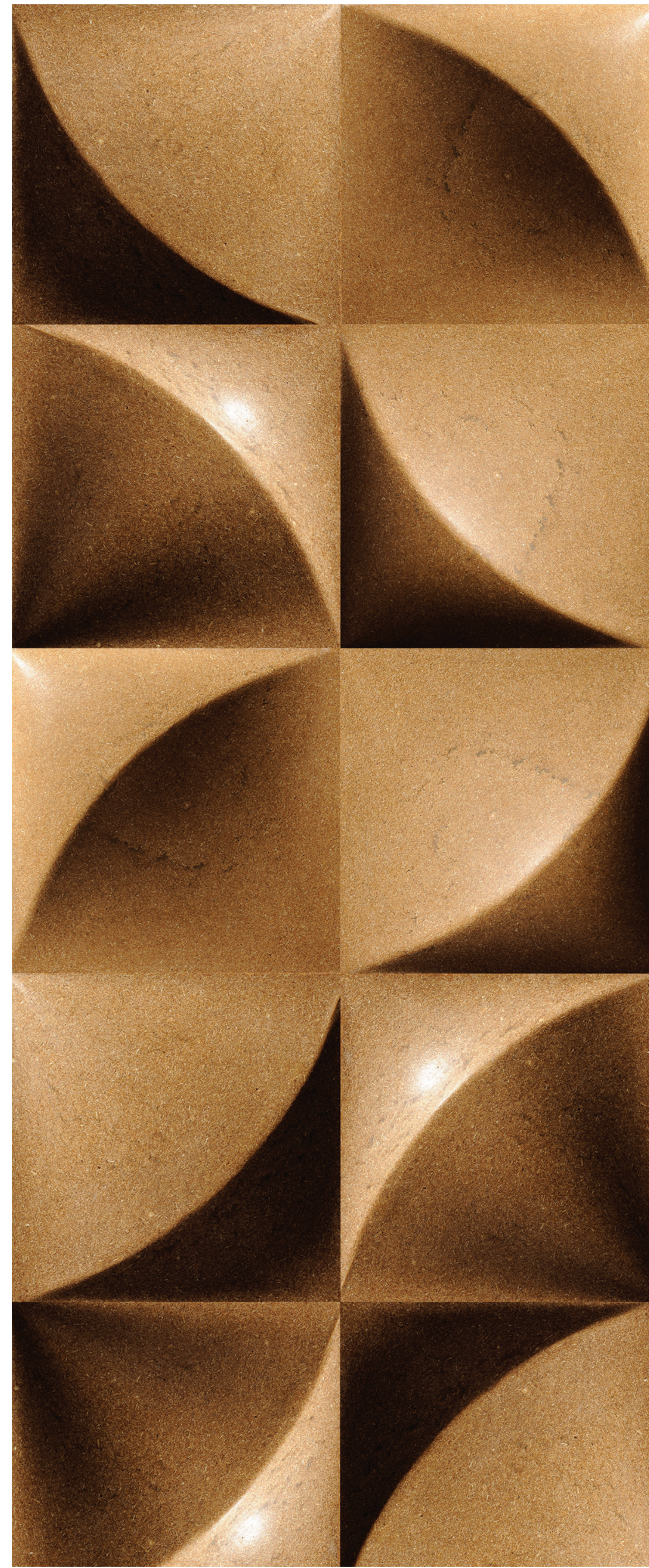

Hanaa Dahy

Agro-fibres Biocomposites‘
Applications and Design Potentials in Contemporary Architecture

Case Study: Rice Straw Biocomposites

Forschungsberichte

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Agro-fibres Biocomposites' Applications and Design Potentials in Contemporary Architecture

Case Study: Rice Straw Biocomposites

von der Fakultät Architektur und Stadtplanung der Universität Stuttgart
zur Erlangung der Würde eines Doktor-Ingenieurs
(Dr.-Ing.) genehmigte Abhandlung

Vorgelegt von
Hanaa Dahy
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Stuttgart, 2015

“We should be taught not to wait for inspiration to start a thing. Action always generates inspiration. Inspiration seldom generates action.” - Frank Tibolt

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Hanaa Dahy

Stuttgart, 2015

Contents

Summary

Out of awareness of the global environmental factors, sustainability principles, eco-efficiency and architectural needs, an investigation of the straw potentials in building industry is thoroughly carried out in this research. Rice straw (RS) is selected as an example of agricultural plant residues fibres, agro-fibres, which are worldwide available, but still though burnt in huge amounts in open fields causing high potentials loss, described in energy, and fiber-resource destruction in addition to the local air pollution and climate change.

Classic straw-bale applications in the building industry do not absorb the available straw amounts and still have many technical and aesthetic drawbacks. Accordingly, it was suggested hereby to apply straw as a main biocomposite ingredient, whether as a fibre-source or as an eco-filler.

Three main biocomposite forms of rice straw and organic polymers' compositions were developed throughout this research. Then they were tested and analyzed for their architectural applications' possibilities according to their technical properties. Firstly, rice straw fibreboard with elastic binder of high fibre load of 80% wt. was developed, and was proved to have high economic and ecologic relevance for its possible architectural applications, that are still not covered by other available fibreboards in the contemporary market. Secondly, green RS thermoplastic biocomposites were developed, were RS was mainly applied as a silica enriched eco-filler- at 20% wt.- to evaluate it as a flame-retardant additive in collaboration with bioplastics in specific. RS-PLA and RS-Lignin green biocomposites were proved to have an elevated fire material class, upon RS fibre's appliance at 20%wt. RS-Lignin biocomposite's fire class changed after compounding the rice straw instead of cellulose with lignin, while RS-PLA enjoyed much better flame-resistance performance, in comparison to RS-PP which was far beyond classification. These results form a new scientific contribution in this field that was not previously addressed in former researches. Thirdly, green RS thermoset biocomposites were developed, where RS was compounded at 20% wt. fibre content with two bioresins using different processing technologies depending on the bioresin's nature, then compared at the same fibre load to RS-fossil-based resin of the same epoxy-base. The comparisons revealed that the green RS-bioresin biocomposites were not particularly mechanically better than the RS-fossil-based biocomposite. However, the former green thermoset biocomposites recorded high free-weathering resistance when pigmented. This could have a high relevance in achieving complex geometrical applications with innovative designs for facades, using these environmentally friendly materials.

The three developed rice straw-based biocomposites provide another aspect of the possibility of applying agro-fibres in sustainable building industry. Fibre-based industries, including fibreboards' manufacturing and molded natural fibre reinforced composites can depend on straw agro-fibres as a main available and cheap fibre-resource. Hence, cheaper and more environmentally friendly biocomposite products could spread in the architectural applications, reducing the total carbon dioxide footprint and replacing expensive fossil-based and slow renewable wood products that are still widely spread in the markets.

Zusammenfassung

Aus dem Bewusstsein für globale Umweltbedingungen, Nachhaltigkeitsprinzipien, ökologische Effizienz und architektonische Bedürfnisse heraus wurde in diesem Forschungsvorhaben das Potenzial von Reisstroh in der Bauindustrie sorgfältig untersucht. Reisstroh (RS) wurde als Beispiel für faserigen Pflanzenabfall gewählt, da diese Naturfasern weltweit zur Verfügung stehen, aber immer noch in großen Mengen auf den Feldern verbrannt werden. Die Zerstörung des Nutzbaren Pflanzen Materials führt zu Verlust von Energie, gleichzeitiger Luftverschmutzung und negativer Klimaveränderung.

Bisher finden bereits Strohballen in der Bauindustrie Verwendung. Diese können jedoch die verfügbaren Strohmengen nicht aufnehmen und haben technische und ästhetische Nachteile. Demzufolge wurde hier vorgeschlagen, Stroh als Hauptbestandteil eines Bioverbundwerkstoffes anzuwenden, sowohl als Faserrohstoffquelle, als auch als ökologischen Füllstoff.

In diesem Vorhaben wurden drei Bioverbundkunststoff-Gruppen aus Reisstroh und organischen Polymeren entwickelt. Die technischen Eigenschaften dieser Proben wurden auf ihre Verwendungsmöglichkeit in der Architektur hin getestet und analysiert. Zunächst wurde eine Reisstrohfaserplatte mit elastischem Binder und einem Faseranteil von 80% entwickelt. Diese erwies sich von hoher ökonomischer und ökologischer Bedeutung für eine mögliche architektonische Anwendung, die bisher erhältliche Faserplatten so nicht aufweisen. In der zweiten Baustoffgruppe wurden zwei thermoplastische RS- Biokomposite entwickelt, denen Reisstroh zu 20% Gewichtsanteil eines mit Silikat angereicherten Öko-Füllstoffs beigegeben wurde, um es als brandhemmendes Additiv im Zusammenwirken speziell mit Biokunststoff bewerten zu können. Biokomposite mit RS-PLA und RS-Lignin zeigten erhöhte Flammbeständigkeit aufgrund des 20%igen Fasergewichtsanteils. Die Entflammbarkeit von RS-Lignin-Biokomposit erreichte eine andere Materialklasse, nachdem Zellulose durch Reisstroh ersetzt wurde. RS-PLA wies erhöhte Flammbeständigkeit im Vergleich zu RS-PP auf, das weit unterhalb der Klassifizierung lag. Diese Ergebnisse leisten einen neuen wissenschaftlichen Beitrag auf diesem Gebiet, was bisher so nicht untersucht wurde. Als drittes entstanden zwei RS–Bioharz-Biokomposite, in denen 20% Gewichtsanteil RS-Fasern mit zwei Bioharzsystemen gemischt wurden. Dabei verwendete man je nach Art des jeweiligen Harzes unterschiedliche Herstellungsmethoden. Es fand ein Vergleich zwischen einem entsprechend zusammengesetzten RS-Biokomposit mit auf Erdöl basierendem Harz statt. Diese Gegenüberstellung machte deutlich, dass die RS-Bioharz-Biokomposite mechanischen Belastungen nicht so gut gewachsen waren wie RS-erdölbasierte Biokomposite. Dennoch zeigten die RS-Bioharz-Biokomposite eine hohe Witterungsbeständigkeit, wenn sie pigmentiert waren. Das könnte von großer Bedeutung sein, wenn diese umweltfreundlichen Materialien für Fassaden mit komplexen geometrischen Formen eingesetzt werden.

Die drei entwickelten Reisstroh Biokomposit-Gruppen zeigen weitere Anwendungsmöglichkeiten von Fasern aus landwirtschaftlichen Reststoffen in der nachhaltigen Bauindustrie. Faser verarbeitende Industrien, wie Faserplattenherstellung und Produktion geformter naturfaserverstärkter Komposite, können Strohfasern aus der Agrarproduktion als sehr ergiebige und preiswerte Rohstoffquellen nutzen. Folglich kann durch die Verbreitung von billigeren und umweltfreundlicheren Biokomposit-Produkten in architektonischen Anwendungen die Gesamt-CO2-Bilanz verbessert und teure fossile Rohstoffe und langsam nachwachsende Holzprodukte, die noch immer den Markt bestimmen, ersetzt werden.

Abbreviations

Cell.	Cellulose
FAO	Food and Agriculture Organization of the United Nations
HDF	High-density fibreboard
HDPE	High-density polyelthylene
Lig.	Lignin
MA	Maleic anhydride
MDF	Medium-density fibreboard
MDI	Methylene diphenyl diisocyanate
NF	Natural fibre
NFRC	Natural fibre-reinforced composites
PHB	Polyhydroxybutyrate
PLA	Polylactide
PP	Polypropylene
PVC	Polyvinyl chloride
RH	Rice husk
RS	Rice straw
UF	Urea-formaldehyde
UV	Ultraviolet
WF	Wood fibre
WPC	Wood-plastic composites
Wt.	Weight

A.

Introduction

A. Introduction

A.1. Agro-fibres as a main component in biocomposites

Agro-fibres is a term to describe agricultural plant residue fibres. Cereal straw is the highest available agro-fibre worldwide. Rice straw (RS) is a selected type of cereal straw that is applied in the agro-fibre biocomposites developed in this research, Fig.(A-1).

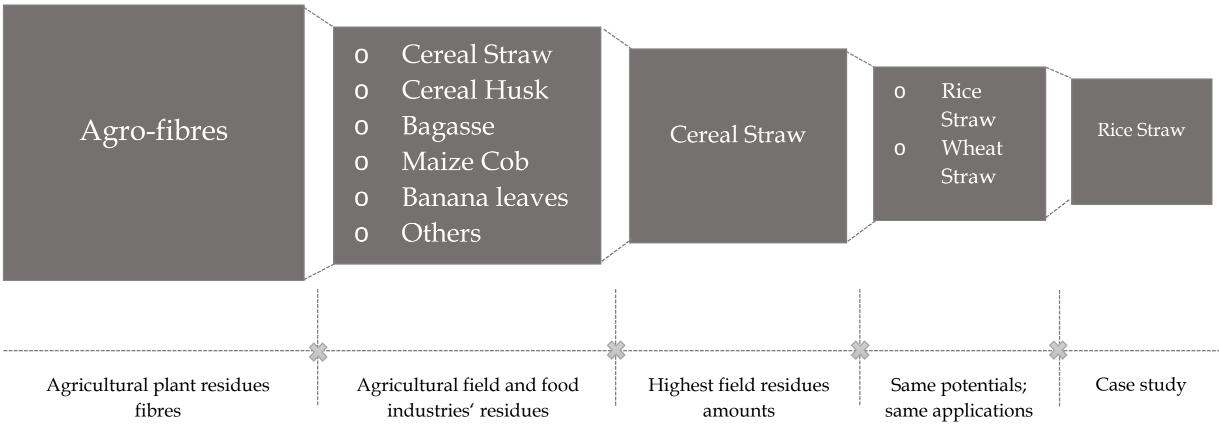


Figure A-1. Illustration of the agro-fibre applied within the research

Throughout the past two decades natural fibres have been applied in many applications and industries including automotives, aircraft, paper industries, textiles as well as building and construction industries replacing, thanks to their lightweight and renewable nature, the non-renewable glass and other artificial fibres in the biocomposites' scope.

Biocomposites is a term used here to describe a composition of a fibre and a matrix (binder), where at least one of them is of a *lignocellulosic biomass- basis* (i.e. plant-based material); while *green biocomposites* is a term that is used to describe that both main components of the biocomposite are lignocellulosic biomass-based. Biocomposites include fibreboards and natural fibre reinforced composites, whether with thermoplastic or thermoset polymeric matrices. Agro-fibres and thermoplastic polymers combinations in the form of biocomposites are sometimes referred to as *agro-plastics*, which is the term used here in the research to describe these biocomposites' type. Green agro-plastic biocomposites is one of the main targets in the research, that is reachable through combining the selected agro-fibre with *biopolymers*, including *bioplastics* and *bioresins*. *Bioplastics* is a term applied according to the European Bioplastics e.V. that defines thermoplastic biomass-based polymers whether biodegradable or not in addition to bio-degradable fossil-based derived thermoplastic polymers. Biodegrading and composting definition is set according to the DIN EN 13432, (Deutsches Institut für Normung e.V. (DIN), 2000); regardless of being derived from a lignocellulosic biomass-basis or petrochemical fossil-basis. *Bioresins* is defined by (Fowler, et al., 2007), as being an emerging thermoset technology that is mostly derived from vegetable oils, with low environmental impact and an alternative to existing *fossil-based resins*. In this research, agro-fibre biocomposites will be developed, using cereal straw fibres. The biocomposites developed are in the form of straw-based fibreboard with an elastic binder, green straw-based thermoplastic biocomposites with improved flame-resistance for interior applications; as well as green straw-based thermoset biocomposites for interior and exterior applications.

Until now, the biocomposites field is more than overwhelmed by industrial natural fibres, including wooden fibres above all, as well as jute, flax, cotton,…etc., while on the other hand natural fibres that are the result of the agricultural residues sector are still valued lowly and unfairly despite their huge advantages and potentials.

Wood consumption worldwide became questionable since the late 20th century. This is due to the international trend of preserving the forests and retaining the needed eco-life equilibrium through changing the forestry behavior and the amounts of consumed wood annually, (McNutt, et al., 1992). Accordingly, searching for an available cheap source of a renewable natural fibre source became an international demand.

Whereas the use of fibre crops planted specifically as a source of fibre is at least questionable from both social and environmental perspectives, the same cannot be said for agricultural residues. Agro-fibres can be applied as a main component in biocomposites, Fig. (A-2), and as seen here, suggested and applied.

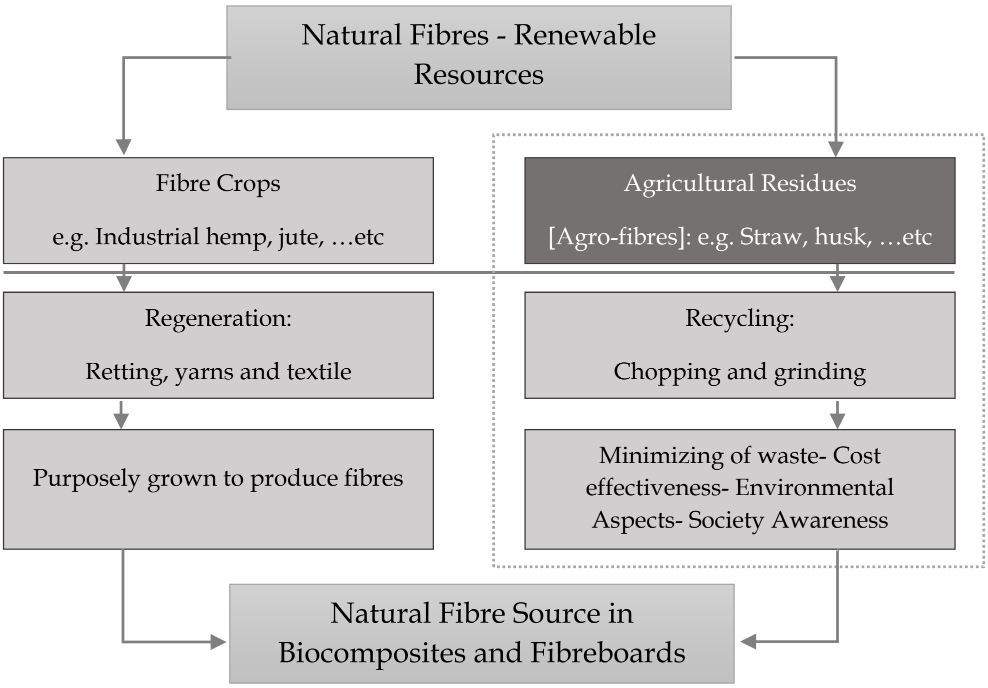


Figure A-2. Non-wood natural fibre sources applicable in biocomposite manufacturing

A.2. Problem definition

Straw, the stem of the cereal plant that remains after the seed needed for nutrition is removed, composes about half the total dry weight of the crop (Sun, 2010). Generally, for every ton of cereal production world-wide, about 1.5 tons of straw as well as other fibrous by-products including sheaths and leaves are left-over as agricultural by-products in the open fields.

The main interest in such annual crops' agriculture is the seed itself- the cereal grain- and not its residues left over after harvesting. That is why huge quantities of agro-fibres accumulate in the fields after re-using relatively small amounts of them in conventional or energy-applications. In case of straw, the huge volume inspite of the low density, is a big problem, unlike other types of crop plants, where after cultivation biomass of smaller volumes are released in the form of stalks as in the case of maize, or bagasse in case of sugar cane, whose volume problem is not as huge as in the straw's case.

As a rapid solution for clearing up the open fields from accumulated straw, many farmers worldwide burn the straw un-officially, causing a seasonal repetitive environmental problems, Figs.(A-3, A-4, A-5, A-6).

Figure A-3. Cereal straws burnt illegally in Worley-Idaho – USA. ***Photo credit: Jessica Caplan / SAFE © 2013 Earthjustice*** **(earthjustice.org, 2005)**

Figure A-4. Rice straws fields burnt in Central China's Guizhou province. (china.org.cn, 2011)

Figure A-5. Open-field rice straw burning near Sueca (Valencia)-Spain, after (Wong, A.- Arbokem Inc., 2011)

Figure A-6. Cereal straws fields burnt in Chile-South America. (Matt, 2012)

The lack of governmental coordination between the farmer and the target industry whether paper industry, energy and bio-gas, building industry or others, represents the main problem of the whole straw management system failure and this is one of the main reason behind the slow-rediscovery of straw's potentials as a fibre-supply. Digging out the positive potentials of solid wastes in specific, after following planned waste management strategies and directing them positively towards building industry, can provide the needed sustainability. Sustainability in this case can be enhanced when environmental-friendly alternative building materials replace the traditional ones, those which cause the rapid consumption and destruction to our natural non-renewable resources.

A.3. Goal

Applying agro-fibres as a main component in biocomposites and green biocomposites to achieve cheaper environmentally friendly materials with higher flame resistances and architectonic values for interior and exterior architectural applications.

A.4. Cereal straw potentials

A.4.1. Availability, renewability and price

Cereal cultivation worldwide covers almost 697,678.673 hectars. (The World Bank Group, 2013) and cereal grains compose up to 72% of the world's agricultural crops' supply, according to the United Nations Food and Agricultural Organization (FAO) in 2007.

Asian countries as seen in Fig. (A-7), release the highest percentages accordingly from cereal straw, then comes North America then the European Union then South America, then North Africa and the Middle East come together in the fifth rank.

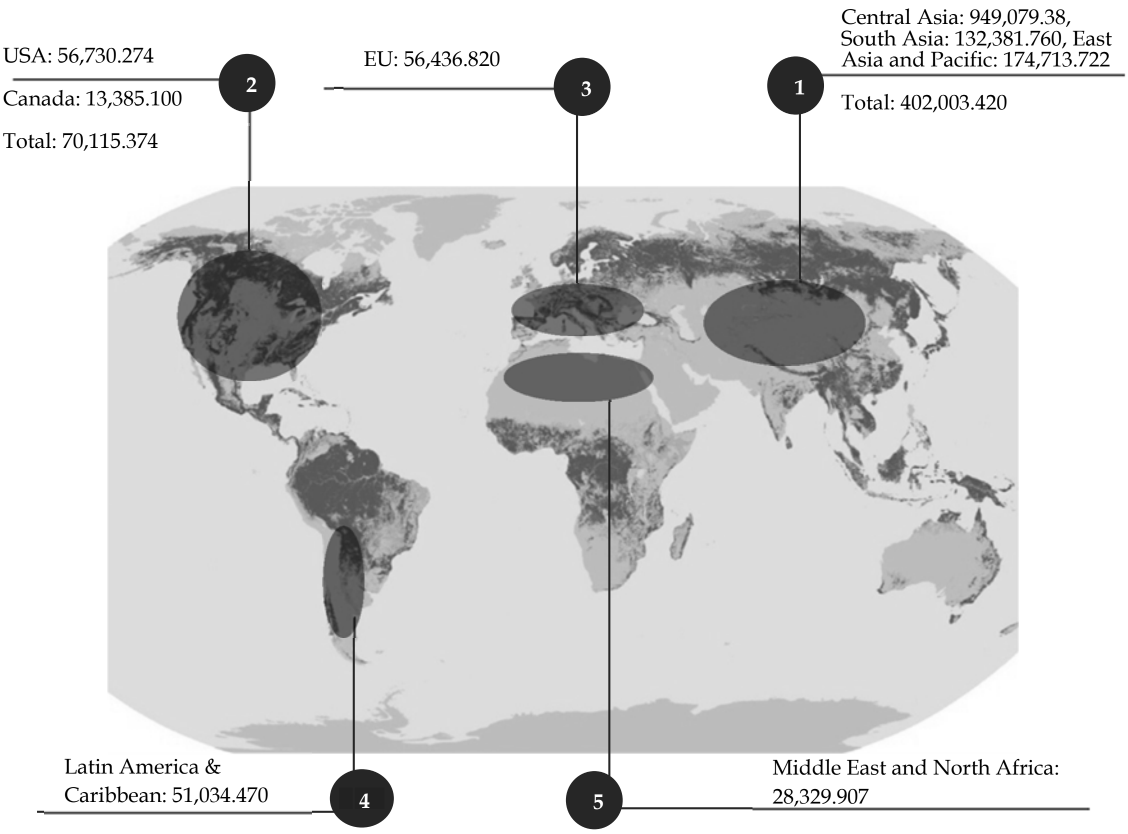


Figure A-7. Land under cereal production (hectares)- Derived from available digital data of FAO+World Bank 2011 (all income levels) (The World Bank Group, 2013)-*Map Photo credit: FAO©-2006*

The total amount of cereal production in 2010 is approximately 2422 million of metric tons, whereas the highest cereal crops' productions are the maize, rice and wheat respectively, forming around 87% of the whole cereal annual production.

Fibre-based industries are in great thirst to new available and rapidly renewable cheap fibre types. The steady increase in the demand of the wood fibre is gradually leading to a worldwide shortage of wood fibre supplies. Since the 1980's, depletion of the world's forests has steadily increased the price of raw wood and wood-based products (Sun, 2010). Through the following table, Table (A-1), a detailed illustration of a number of the main industrial natural fibres worldwide, compared with cereal straw economically and technically, is given. To evaluate the general technical values and prices of the natural fibres, a comparison with the artificial glass fibre is also given.

Fibre Source	Stem fibres					Leaves fibres		Fruit fibre	Shells-Husks	Glass fibre (16)
Name/ Property	Flax	Hemp	Jute	Cereal Straw	Wood	Sisal	Banana	Cotton	Coir	
Ultimate Tensile Strength [10^3 N/mm^2]	0.35-1.5 (1)	0.69 (1)	0.39-0.8 (1)	0.009-0.04 (4), (5), (6); ca. 0,12 (7); (M.S.) 0.13-0.4 (8)	(L.) 0.088-0.132 (18)	0.47-0.7 (1)	0.095 (12)	0.29-0.8 (1)	0.13-0.22 (1)	1.4-2.7
E-Modul [10^3 N/mm^2]	27.6 (1)	70 (1)	13-26.5 (1)	(M.S.) 26 (9)	10.78-15.69 (18)	9.4 – 22 (1)	1.4 (12)	5.5-12.6 (1)	4-6 (1)	73-75
Ultimate Strain [%]	2.7-3.2 (1)	1.6 (1)	1.16-1.5 (1)	(M.S.) 2.2 (9)	-	3-7 (1)	5.9 (12)	7-8 (1)	15-40 (1)	2.0-4.8
Density [g/cm^3]	1.5 (1)	1.47 (1)	1.3-1.49 (1)	0.02-0.72 (10)	0.43-0.68 (18)	1.45 (1)	1.35 (12)	1.51 (14)	1.15-1.46 (1)	2.5-2.7
Price ca. (US$/ Ton)	440->730 in 2003 (2)	550->880 in 2003 (2)	477-716 in 2000* (3)	41 in 2008 (11)	S.W.:88-108; H.W.: 83-106 (bet. 2005-2008) (19)	1030 in 2003 (2)	430-810 in 2008 (13)	1652 in 2013 (15)	239-477 in 2000* (3)	2000-3000 in 2013 (17)

References: (1): (Bismarck, et al., 2005) ; (2): (Natural and Wood Fiber Composites Newsletter, 2003) ; (3): (Karus, et al., 2000); (4): (O'Dogherty, et al., 1995); (5): (O'Dogherty, 1989); (6): (Limpiti, 1980); (7): (Kronbergs, 2000); (8): (Shang, et al., 2012); (9): (Reddy, et al., 2006); (10): (Jenkins, 1993); (11): (Prairie Practitioners Group Ltd. in association with The Composites Innovations, 2008); (12): (BMTPC (Building Materials and Technology Promotion Council)); (13): (Mukhopadhy, et al., 2008); (14): (Baunetz Wissen-Glas); (15): (Index-Mundi, 2013); (16): (Youngquist, 1996); (17): (NetComposites); (18): (Bogusch, 2005); (19): (Wood Resources International LLC (WRI), 2008)

Abbreviations: (M.S.) : Modified Straw- textile industry; (L.) : Longitudinal direction; S.W.: Softwood; H.D.: Hardwood; bet.: between

Table A-1. Mechanical, physical characteristics and price evaluation of natural plant fibres in comparison with glass fibres.* Currency was transformed using historic currency transformer program (OANDA(R) Corporation).

Cereal straw's tensile strength varies widely according to the modification technique applied on the straw fibre, starting from 0.009 uptill 0.4x10^3 N/mm^2, which reflects the possibility of competing with other natural industrial fibres like flax, sisal and jute. Straw enjoys the lowest density among all other natural fibres' types, and the lowest price. This forms together high economical potentials that promotes this fibre to highly compete in different fibre-based industries, including biocomposites' manufacturing.

A.4.2. Special chemical composition

Cereal straw has the highest silica contents within all plant species; where rice straw has (9-14%) after (Kocurek, et al., 1983), (Pekarovic, et al., 2008), and in some cases can reach till 20% (Yang, et al., 2006), (Buzarovska, et al., 2008). Secondly comes wheat straw with (4-10%), (Pekarovic, et al., 2008) , while wood has less than 1% silica contents, (Kocurek, et al., 1983).

Chemical composition of cereal straw (including rice and wheat straws) in comparison to wood, in percent of dry matter, can be described within Table (A-2) as follows:

Lignocellulosic Biomass		Density [g/cm³]	Cellulose	Hemi-cellulose	Lignin	Silica	Ash	Fibre Size and Aspect Ratio
Cereal straw	Rice straw	0.02-0.72 (1)	28-36 (3)	18–25 (4)	12-16 (3)	9-14 (3), (6); 15-20 (11), (12)	15-20 (3)	D=5-14 µm (7), L=0.65-1,3mm (8), AR=16.3 (9)
	Wheat straw	-	38-46 (3)	20–32 (4)	16-21 (3)	3-7 (3) /4-10 (6)	5-9 (3)	-
Wood	Soft wood	1.53 (2)	40-45 (3)	7-12 (5)	26-34 (3)	- (3)/<1 (6)	<1 (3)	D=50 µm, L=3mm, AR=60 (10)
	Hard wood	-	38-48 (3)	20-25 (5)	23-30 (3)	- (3) /<1 (6)	<1 (3)	-

References: (1): (Jenkins, 1993); (2): (Summer, 2000); (3): (Kocurek, et al., 1983); (4): (Galletti, et al., 2011); (5): (Chander, et al., 2007); (6): (Pekarovic, et al., 2008); (7): (Rowel, et al., 1997); (8): (Wasylciw, et al., 1998), (9): (Ming-Zhu, et al., 2011); (10): (Forest Products Laboratory, University of California, 2000); (11): (Yang, et al., 2006), (12): (Buzarovska, et al., 2008)

Table A-2. Comparison between chemical and physical composition of cereal straws (rice and wheat) with wood (soft and hard). ***D= Diameter, L= Length, AR= Aspect Ratio***

Rice straw, the chosen agro-fibre to be applied in the developed biocomposites in this research, is the second highest cereal straw as seen in Fig.(A-8).

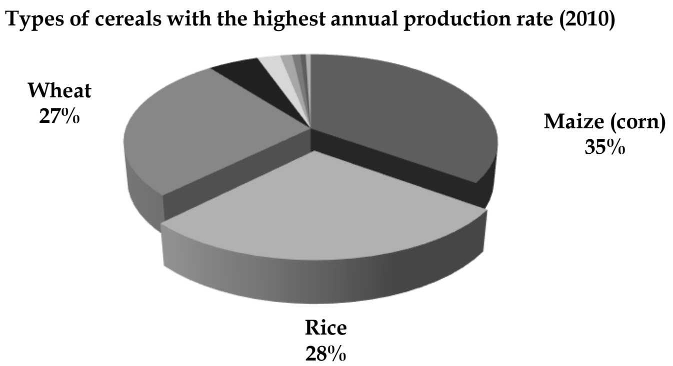


Figure A-8.Percentagesof the highest crops 'production rates for the year 2010. (Data derived from FAO 2010)

Through the previous comparison, cereal straw potentials in comparison to wood are revealed as follows:

- The high silica contents, which are of great potentials when applied as a flame retardant, replacing traditional ones within building materials' manufacturing (Buzarovska, et al., 2008). In addition, silica works against rapid biodegradability which can be of much higher potentials when combined with biodegradable bioplastics, to increase the life time span and enhance durability within the green biocomposite building materials.
- Lower lignin contents are as well a factor that shows the non-tendency towards rapid combustion as in the case of soft and hard-woods.
- Straw has very high potentials for substituting wood, especially in fiberboards' manufacturing inspite of having slightly shorter fibre length, since the chopped straw flakes have uniform surfaces without telegraphing when wetted within processing,(Wasylciw, et al., 1998).

A.5. Research scope and target countries:

Since rice straw has the highest silica contents within cereal straws, it has been chosen to be applied as a fire-retardant eco-filler within the developed biocomposites throughout the research.

Research's scope and target countries in which the research's outcome can be applied in are:

i. Asian countries including Japan, China, Thailand, Malaysia, Indonesia and India, where green agro-fibre biocomposites' resources are available including both the agro-fibres' resources and the biopolymers' expanded contemporary and future markets, (IfBB Statistics, 2013). Therefore applying green agro-fibre biocomposites, that are through this research studied and developed, can be applied in higher quantities in architectural applications, compensating the un-willingness there to spread in straw-based housing systems through direct reuse of straw-bales, as discussed in the state of the art chapter.
ii. European countries, especially the United Kingdom, Austria, Sweden and Germany - where agro-fibres applications in building industries receives high interest and is continuously spreading. In addition, the large existing biopolymer market can further spread by replacing the expensive biopolymers with the cheap suggested fibre, which is highly needed in the contemporary European biocomposites' markets.
iii. North- and South-American countries including the USA, Canada, Mexico, Brazil, Columbia and Peru with the readily available rice and wheat straw amounts in addition to the biopolymers growing markets, (IfBB Statistics, 2013).
iv. African and Middle-East countries including Egypt, Tunisia, Algeria, Lebanon, South-Africa…etc, where plastics' applications in building industries are increasing, hence applying straw as a filling material for fossil-based plastics within architectural applications would be possible, decreasing prices and attracting greater market interests.

As illustrated, the research outcome is expected to meet interest when evaluated in different countries worldwide, since straw's availability covers all continents, while plastics and polymers' technologies exist in almost all countries worldwide, regardless of the technological level of each and the income level of the inhabitants.

A.6. Research hierarchy

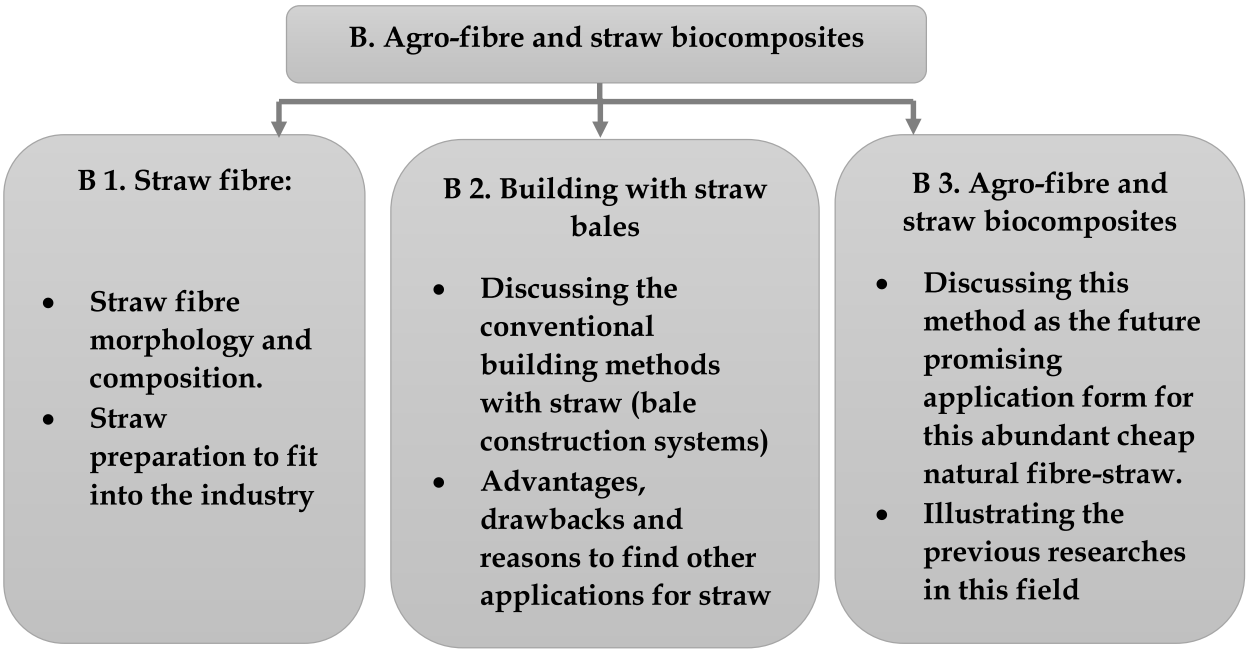
	Chapter Identification	Chapter Parts	Main topics, targets and comparisons
Theoretical investigation	A. Introduction		
	B. State of the Art	B1. Straw fibre	
		B2. Building with straw bales	
		B3. Agro-fibre and straw biocomp.	-Agro-fibre and straw fibreboards -Agro-plastics and straw thermoplastic biocomposites -Agro-fibre and straw thermoset biocomposites
FURTHER APPROACH IDENTIFICATION			
Experimental investigation and analysis	C. Rice Straw Biocomposites Developments	C1. RS fibreboard with elastic binder	-Properties analysis of RS-fibreboard. Properties of the developed fibreboard are compared through the following comparison criteria: RS-elastic binder; Fibre content wt. variations: 20%, 40%, 60%, **80%** (TARGET)
		C2. Green RS thermoplastic biocomposites	-Properties analysis of two RS-thermoplastic biocomposites at **20%wt**. RS. Properties validation through the following comparison criteria: RS - PLA (20%wt., Biomass-based bioplastic) TARGET; RS - PP (20% wt., Fossil-based plastic); RS - Lignin (20%wt., Biomass-based bioplastic); Cel- Lignin (20% wt., Biomass-based bioplastic)
		C3. Green RS thermoset biocomposites	-Properties analysis of two RS-thermoset biocomposites at **20%wt.** RS. Properties validation through the following comparison criteria: RS- Gripox (20%wt., Bioresin that hardens in room temp.); RS - PTP (20%wt., Bioresin that hardens in high temp.) TARGET; RS Epikote (20% wt., Fossil-based resin that hardens in room temp.)
Deduction, analysis and conclusion	D. Architectural Applications	D1. Applications of RS-fibreboards with elastic binder- 80%wt.	- Planar flooring applications - Bending concepts: 3D and free-form applications
		D2. Applications of green RS-thermoplastic biocomposites	- Interior free-form cladding elements - Mono-block lightweight sandwich panels - Interior screens, space-dividers and false-ceiling
		D3. Applications of green RS-thermoset biocomposites	- Exterior free-form and pigmented façade panels
	E. Conclusions & Recommendations		

B.

State of the Art

B State of the Art

In this chapter, analysis of the chosen agro-fibre, its composition, conventional application methods in architecture and the promising contemporary and future application methods are discussed. Previous research work is thoroughly illustrated and conclusions concerning the impact of this on the applied developments in this research work is illustrated at the end of each part. This chapter is divided into three parts, as follows:

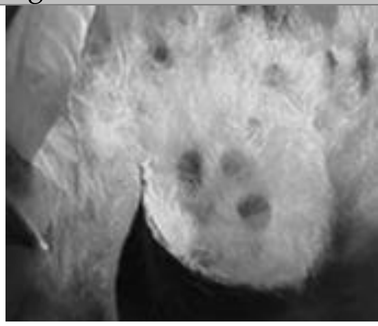


B 1. Straw fibre

B 1.1. Natural fibres and straw

Straw is a plant-based natural fibre. Generally, natural fibres are either animal-based as wool, silk, mohair,…etc; plant-based as wood, bagasse, flax,…etc; or natural mineral based material as asbestos, rock wool,…etc.

Plant-based fibres are themselves morphologically subdivided into different types according to the part of the plant, from which the fibre has been originated. This includes plant-seed, -leaf, -bast, -stem/stalk and -fruit. Straw belong morphologically to the stalk or stem part of the plant, as illustrated in the following table:

Fibre Source	Description	Figure
1-Fruit fibres	Fibres are collected from the seed of the plant. The seeds in this case are attached to hairs and encased representing the inner plant part. Cellulosic contents vary greatly according to the plant type. Ex.: Cotton, Kapok	 **Kapok fibres** ***Photo credit: (www.how2behealthy.info,2010)***
2-Leaf fibres	Fibres are collected from the leaves. Most fibres generated here belong to the agricultural residues category as they result from a cutting process that should occur to enable the normal plant growth and cultivation for nutrition purposes. Ex.: Banana, Sisal	 **Sisal plant.*Photo credit: Rhett Butler, 2004(wildmadagascar.org)***
3- Stem fibres		
3-a. Bast-/ Stalk- / stem-skin	Fibres are collected from the surroundings of the plant's stem (stem's skin).This type is the highest consumed one among plant fibres within the industrial applications and are mostly planted to gain the fibre itself and not for nutrition purposes due to their high tensile properties (fibre crops). The fibre is integrated with natural gum in the plant structure. Removal of this gum is made in a process called, 'retting' (Mishra, 2000), where bacteria and natural-occurring fungi is applied to remove lignin, pectin and other impurities on the cellulose-fibres that need to be extracted. These conventional methods take a lot of time, therefore for economic reasons these natural methods are mostly replaced by chemical methods, especially using sodium hydroxide (NaOH), or through mechanical methods using decorticating machines as well as steam explosion (STEX) in addition to ammonia fibre extraction methods, (Reddy, et al., 2005). Ex.: Hemp, jute, ramie, kenaf (industrial natural fibres)	 **Jute plant's stem being retted and separated, *Photo credit: (International Natural Fiber Organization.).***

3-b.Stalk	Bark or stem's skin in this case is thin and cannot be extracted to form a fibre of its own as in the previously mentioned case, except using special techniques to extract microfibrils that can be applied in textile industries, (Reddy, et al., 2006), but this technology is still not commercialized. Therefore, the most common method is applying the whole plant stem as a fibre source after chopping it, and applying it after pre-treating or without, as will be discussed later in the following chapter. This type includes as well trees trunks, the main supply of wood fibres; as well as annual plants' stems that are left over in fields after harvesting. Ex.: Cereal straw, trees trunks	 **Straw fibre .*Photo Credit: Dahy, H.***
4- Fruit shell/Husk fibres	This husk protects the fruit during its growth. Fibres can be extracted, retted and processed. In some cases, husk is so small, so it can be grounded or applied in a short fibres-form. Ex.: Coconut (Coir), Palm-nut, Rice husk	 **Coconut husk/ shell – Coir fibre *Photo Credit: Kitthongplew, Phuwadet, 2012 (coconut shell-fineartamerica.com)***

Table B1-1. Plant fibre sources according to plant parts from which the natural fibre is derived.

B 1.2. Morphological composition

Annual cereal plants like rice and wheat are less homogeneous morphologically in comparison to the lasting softwoods and hardwoods. Straw is considered the structural material that leads the whole plant to stand up.

Concerning the chosen cereal straw, rice straw, is gained from a plant that varies widely from 100 to 180 cm and diameter of approximately 5 mm, with long leaves ranging from 50-100 cm and 2-2.5 cm breadth, depending on species and cultivation methods that take from 3-6 months (University of Queensland and the International Rice Research Institute, 2003), soil fertility and many other aspects. The top section of the rice straw is branched into nodes and the thretched-out remains of the grain-bearing particle (internodes), as illustrated in the rice plant anatomy figure- Fig. (B1-1).

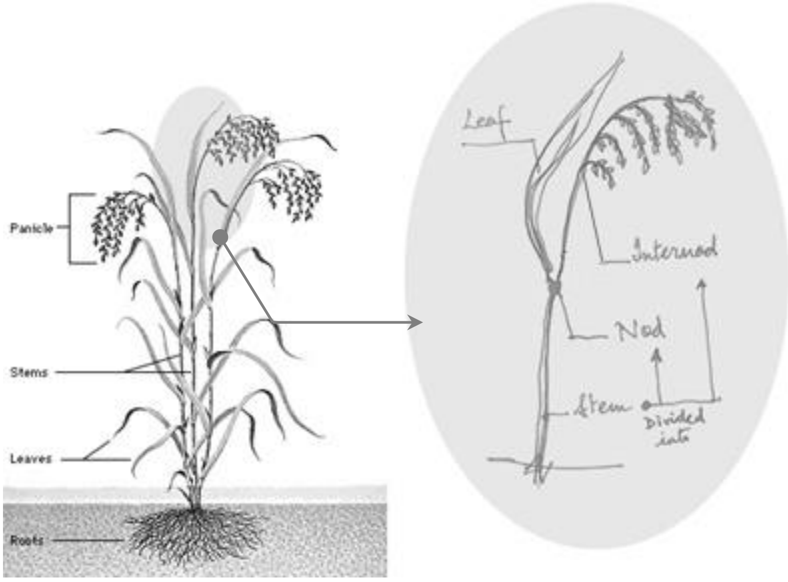


Figure B1-1. Rice plant anatomy (Photo credit: http://science.howstuffworks.com/life/botany/rice-info.htm + researcher [Detail sketch]).

The internodes were found to be the parts with more sufficient fibrous quantities than the leaves and other stem parts, according to (Halvarsson, 2010). Literature states that fibrous tissue in rice straw is estimated to be 46% only in comparison to 67% in wheat straw and in the range of 73-98% in wood (Jin, et al., 2007). Due to this relatively weak structure of the rice straw internodes fibres, a consequent botanic adaptation took place to give the stem extra rigidity to be able to stabilize the whole plant structure and to enable it to hold the grains' weight. This natural adaptation occurred through the deposited silica contents in the plant's epidermis, which is the outermost part of the stem working as its skin and protecting the plant from environmental changes and water loss. That explains and uncovers the reason that rice straw has the highest silica contents within the plants' species. The epidermis being fully loaded by silica, provides the needed rigidity and fungal attack resistance. Furthermore, it is extra surrounded by another thin waxy film of free cutin, which makes the straw fully water repellant from outside and impermeable. (The World Bank Group, 2013)

In both paper industry and fibreboards industries, chemical and thermo- mechanical modifications take place to get rid of these waxy cutin film and epidermis layers to reach the internodes fibrous long fibrils, the rich material needed in such industries. Rice straw fibre after extraction has a length in the range of 0.65-1.3 mm (Wasylciw, et al., 1998) and diameter of 5-14 µm (Rowel, et al., 1997), with an aspect ratio, which describes the proportional relationship between the diameter and the length, that can reach 16.3 , (Ming-Zhu, et al., 2011).

As indicated for such industries, the undesired waxy layers and inorganic silica components are of the highest concerns in how to get rid of, without destructing the fibrous components, as discussed in many researches (Sun, 2010), (NTNU- The paper and pulp group) and others. This was mostly using alkali treatment applications.

This pulping operation is not only complicated and expensive, but results in many chemical by-products including unrecoverable high silica and lignin contents dissolved in the strong alkalis applied (Mantanis, 2001). In addition, many undesired elements could not be totally eliminated inspite of the expensive chemical procedures including epidermis fine layers with some silica contents at the final steps of the pulping process (NTNU- The paper and pulp group). In addition, this process dissolves and ruins many advantageous fibrous layers that are densely packed in the inner side of the epidermis as shown in Figs. (B1-2), (B1-3) for magnified straw internode transverse sections. On the other hand, many other approaches for physically treating the straw for fibre-boards applications were applied, which are much more environmentally friendly. The most common method in handling natural un-modified straw is the chopping method, as suggested by (Mantanis, 2001), (Markessini, et al., 1997) and (Mo, et al., 2003), to open and increase the fibres' interface areas, which is the method applied here in this research.

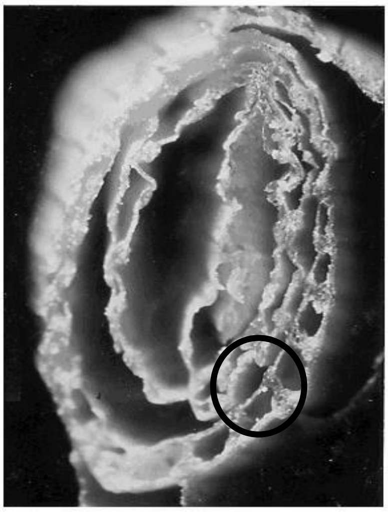


Figure B1-2. A dry rice straw internode transverse section. Photo credit: (NTNU- The paper and pulp group)

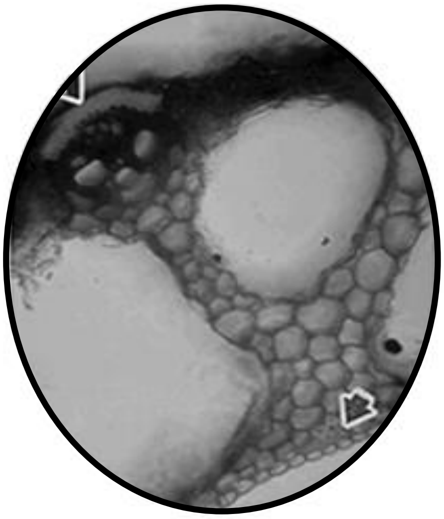


Figure B1- 3. Fibrous cells rigidly attached to the outer skin (epidermis) of the rice straw internodes- Mag. 260x. Photo credit: (NTNU- The paper and pulp group)

B 1.3. Chemical Composition

80% of straw's dry matter is composed of cellulose, hemicelluloses and lignin. Ash is another important component of straw that includes the non-organic matter in the plant tissues including silica - the highest potential of this residue- as here raised in this research.

Through the following points, the inner chemical components of straw are further declared as follows:

B 1.3.1. Cellulose

Cellulose occurs in nature largely in a crystalline form and is organized as fibrils. These fibrils are bonded by very strong hydrogen bonds that can only be disrupted through strong solvents whether acidic or alkali based. The crystalline cellulose core of the cell-wall microfibrils is highly resistant in its natural form to chemical and biological hydrolysis because of its structure, (Sun, 2010 pp. 30-31), Figs.(B1-4), (B1-5).

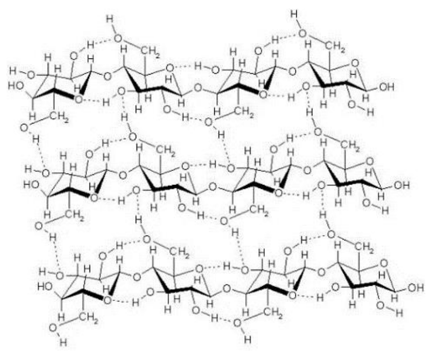


Figure B1-4. Chemical Structure of Cellulose. (Helmberger, 2009)

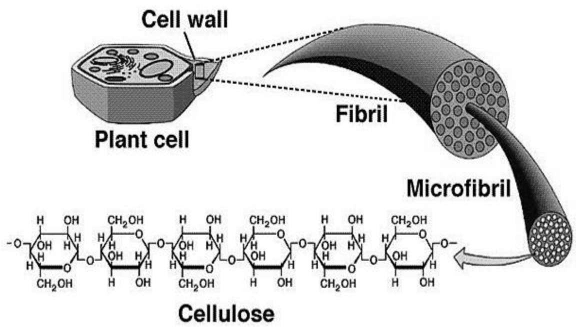


Figure B1-5. Sketch showing the cellulose structure with the cellulose, fibrils and microfibrils arrangement within the fibrous tissues of the plant cell walls. (Moore, et al., 2008)

The accessibility of cellulose to hydrolysis can be also enhanced through physical treatments like milling, to increase the surface area, and steaming. All these methods are used to make cellulose less crystalline and less hindered by accompanying other organic components like lignin and silica.

In general, all previous mentioned isolation methods and inspite of its being strong, cellulose can never be isolated in a pure form, but only in a crude form, (Sun, 2010 p. 34). Cellulose is delignified and isolated through both mechanical and chemical treatments to dissolve and depolymerize the lignin, hemicelluloses and noncellulosic components. When the biomass is applied in paper industry, a black liquor with lignin, silica and other impurities are the result of the trials of cellulose separation and this black liquor goes then afterwards in many expensive treatment procedures to win back those other impurities to be positively used in other industries as well as winning back the chemicals that were used in the treatments themselves.

B 1.3.2. Hemi-cellulose

Hemicelluloses rank the second after cellulose in the abundance of cereal straw, compounding roughly one-fourth to one-third of most of the dry plant materials. Unlike Cellulose, hemicelluloses are much more complex in its structure and are bonded with cellulose through hydrogen bonds, while with Lignin with covalent bonds. In general, they are defined as branched polymers of low molecular weight which consists of many sugar units that are arranged in different proportions, Fig. (B1-6). The biological importance of hemicellulose is its effect on the cell wall's strength, since it bonds with cellulose and in some walls with lignin, (Scheller & Ulvskov, 2010)

There is a great tendency recently in developing biopolymer-based materials derived especially from cereal straw and based on hemicelluloses' extraction. Many researchers succeeded in converting cereal-residues' hemicelluloses to sugar, chemicals and fuel as sources of heat energy. Many applications in both the food and non-food sectors have been reached inspite of the complexity of the hemicelluloses' structure. Gels, films, coatings, stabilizing and viscosity-enhancing additives in food, pharmacy as well as many other industrial branches are examples of the applications of hemicelluloses' applications. (Ebringerova, et al., 2005)

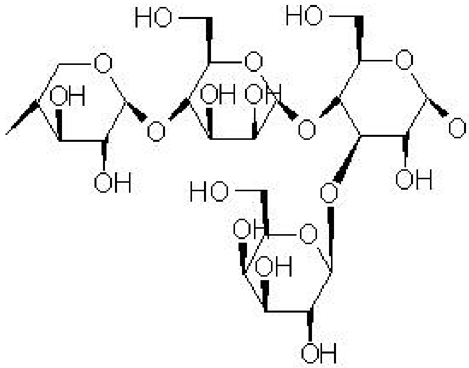


Figure B1-6. Chemical Structure of Hemicellulose. (Helmberger, 2009)

The extraction and isolation procedures can even start from the by-products of the processing of the annual plants. This means that after the processing of the residues as a 'resource' in paper pulping or in textiles' industries, this component can be further isolated from the process water of the paper pulping or through the organo-solv pulping and heat fractionation processes, (Sun, 2010 p. 77).

B 1.3.3. Lignin

Lignin is one of the most abundant organic materials and renewable resources on earth. Lignin which is a family of branched non-carbohydrate polymers, Fig. (B1-7), is a main component of straw and is considered as a composite of physically and chemically heterogeneous materials. The hydrophobic nature and the low content of hydrolysable bonds render lignin very durable, and thus, lignin can serve as a protection against mechanical as well as microbial attack, (Sun, 2010 p. 37). Rice straw lignin is called *p*-hydroxyphenyl–guaiacyl–syringyl (H–G–S) lignin and contains all three monolignol units in significant amounts. Analysis of degradation products following cleavage of ether linkages by thioacidolysis indicates the respective proportions of H, G, and S units in lignins are 15, 45, and 40% for rice straw, (Buranov, et al., 2008) . During maturation of grasses, the syringyl content increases and this make the plant more resistant to fungal infection, (Ride, 1975).

The studies on herbaceous lignin has been increased and attracted recently much more attention than before as previously researches concentrated mainly on lignin derived from wooden origins and not plants. But the huge amounts of annual plants' lignin, reaching up to 1549 million tons annually worldwide, succeeded in attracting much more international attention nowadays (Kim, et al., 2004).

In general, lignin is considered as the cementious composite that hardens and strengthens the structure of the plant, in addition to controlling the fluid flow. This makes lignin's usage as a bio-polymer, in case of its isolation and extraction, of many positive aspects that can be viable in many different industrial applications. These include its being used as leather-tanning agent, and a fuel when burnt within the pulping processing in the paper industry to win back the valuable inorganic pulping chemicals.

In addition, lignin has many positive applications as being utilized as dispersants, binders and adhesives. This later one is especially of great interest especially in furniture and building industry. This adhesive nature of the lignin polymer turns back to its phenolic nature that can enable it easily to replace the PF (phenol Formaldehyde) and UF (urea Formaldehyde) resins that are widely used in wood composite productions, so as to produce a new green formaldehyde-free adhesive. These lignins can be purified and isolated from the lignosulphonates of the liquors resulted from the pulping processes, (Sun, 2010 pp. 194-195).

Within the research, lignin will be combined with rice straw and the manufactured green biocomposite's material properties and the application possibilities in architecture will be thoroughly described**.**

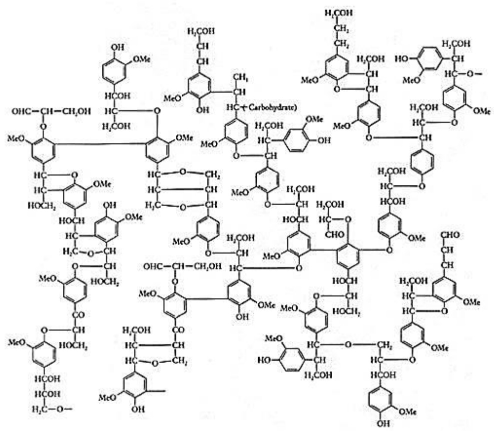


Figure B1-7. Chemical Structure of one of the commom Lignin types, showing complexity of the highly branched structure. (Helmberger, 2009)

B 1.3.4. Ash

Straw's ash consists of the non-organic components of the plant, including around 19 essential minerals for the growth and development of plants. The most important minerals in straw's cell wall are the Si (Silicon), which is distributed in the form of silicon dioxides (Silica), Ca (Calcuim) and P (Phosphorus), (Sun, 2010). The former in specific has proved next to its negative effects on digestion and withdrawal of the plant's usage in feedstock, other positive effects including the contribution in insects- and fungus-resistance, in addition to improving the mechanical properties as well as its natural resistance against flammability.

B 1.4. From field to industry

B 1.4.1. Straw's Transportation

Economically, a conflict might appear as a negative impact of the relatively high transportation costs of the natural fibres due to their low density and huge volume. Therefore, further densification procedures of natural fibres should take place in or next to the agricultural fields before being transported for further manufacturing in different industrial fields, including the building industry.

In case of the rice plant, two types of agro-fibres are available after the plant's harvesting: the field-residue, rice straw, left on open fields; and the process-residue, rice husk, which is collected in the rice mill factories after separating the grain from the outer husk shell. Rice Husk (RH) has many similar potentials as those discussed in rice straw, but it is already collected in a compact way, so the volume problem and transportation difficulties does not exist in the same sense as in the case of rice straw. That's why transportation problem is linked to field-residues specifically, more than to process-residues.

The baling procedure is an essential step to transport the straw from the fields to the industrial plants in densified and standard geometrical forms, whether cylindrical or cubical. Generally, a straw bale is the common unit for straw transport from fields. A better transport solution would be when the straw is further compacted in the form of milled fibres or in pellets form, due to the increase in density in comparison to the volume, as declared afterwards in Table (B1-2).

Before the baling procedure takes place, the straw should be left for enough time to allow the straw to dry naturally to at least 17% of internal relative humidity, to prevent the straw bales to rot and decay (Summer, 2000). The bales can be de-baled and chopped or milled in case of fibreboards' manufacturing and biocomposites industries. Chopping can exist next to the storage areas, or after transporting the bales to the factories of the intended industrialization.

Bales can also be directly applied as constructional units, as discussed in the following part of this chapter. In this case, quality control should take place to ensure the possibility of applying the fibre in the building industrial field, mainly according to the fibre quality, inner humidity, wrapping wires' type and wrapping system. The trip of fibre selection, baling, defining the target industry and quality control requires special experience, the same way as other natural fibres' selection methods. Economically, it is better to store the straw bales next to the fields using one of the economical storage methods for bales, so as to have a regular material supply from straw all year long (Prairie Practitioners Group Ltd. in association with The Composites Innovations, 2008), (Wasylciw, et al., 1998) . This is in case the straw would be applied as a main source for many industries including paper, fibre, particle boards and biocomposites industries. But because straw bales are around 1/3 the density of wood logs, straw transportation's cost is still sensitive in comparison to wood, which makes it essential that the transportation would be integrated with storage (Wasylciw, et al., 1998).

The sequence of straw baling, storing and transporting are indicated in Figures (B1-8, B1-9, B1-10).

Figure B1- 8. Different baling systems (Huisman, et al., 2002). Up: square-bale individual wrapping, Down: Tube-wrapped system

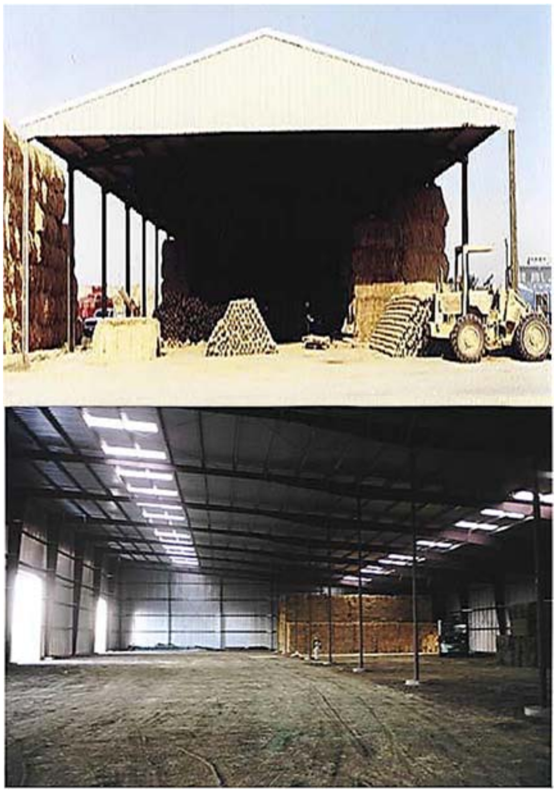


Figure B1- 9. Different storing systems (Huisman, et al., 2002). Up: Pole barn storage, Down: Metal building for closed storage

Figure B1-10. Transporting Straw bales. Photo credit: (FarmEnergy.org, 2009)

B 1.4.2. Straw's physical forms according to processing techniques

a. Baling

Agricultural machines called balers are provided to gather cut crop material from the field after harvesting and secure it together in bundles of cut crop material called "bales". After harvesting, plants are left over and laid in windrows to dry, and then afterwards these windrows are lifted off the field by balers and compacted into bales (Chaney, et al., 2012). After baling, the straw bales are stored to guarantee a continuous fibre feed throughout the whole year.

b. Palletizing/Cubing

One of the methods for condensing biomass is pelletizing. The process of making pellets, especially those that are of high-quality and "binderless" is not an easy one as moisture, heat and size are critical factors.

Until now, the most common pelletized biomass for fuel is wood, mainly from sawdust, wood chips and shavings. Straw became attractive to be pelletized as well to be used as wood-replacement as an energy source. Cubing is a similar method of densification as pellets, but with less bulk density. It can be applied for both feed stock and for energy supply. In case of rice straw, the cubed rice straw applied for animal feedstock should be first treated with ammonia, which is an expensive process, before being transported to the animal farms.

c. Chopping /Milling

It is another method of densification and finding another way of handling the residues in a more dense form that can be packed and commercially used. Milling is a classic known method for physically treating the fibre before applying it as a main raw material in fibre boards making, paper making and biocomposites' manufacturing.

One of the known problems of the chopping procedures is the dust clouds emerged from such a process, Fig. (B1-11). Machinery integration together with a dust-absorbing apparatus, within a field chopping plant, can be a possible solution to such a problem – Fig. (B1-12).

Figure B1-11. Clouds of dust spreading after pilot cutting process of straw.
Photo credit: Prof. Jenkins, UC Davis , after (Bakker, 2009)

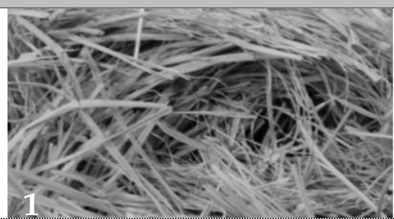
Figure B1-12. The chopping machine is integrated with the collector and dust absorber. (FRITSCH GmbH)

Chopping is preferably applied with the normal inner straw moisture that reaches around 17% after left naturally to dry in fields (Summer, 2000) , to prevent fibre thermal deterioration during chopping (Churchill, et al., 2005). The types mostly used in architectural applications are the first and last ones: baling systems and chopped fibres that are either reused in case of baling or recycled to produce fibre-/particle- boards and bio-composites.

B 1.4.3. Straw's bulk densities according to physical forms

The density of rice straw differs whenever the physical treatment and packaging method differs. This was revealed in many researches especially how bulk density can be a major physical property in designing the logistic system for biomass handling (Lam, et al., 2008).

Through the following table, density values are given to different rice straw physical forms as follows:

Straw Physical Form	Bulk Density (Dry Basis) [Kg/m^3]	Photo	Comment
1- Loose	20-40		Can not be transported – expensive
2- Chopped	40-80		Chopping can take place after de-baling. Main applications: paper, biocomposites and fibreboards

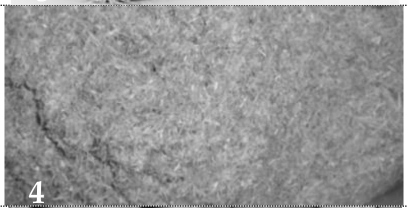
3- Bales	110-200		This is the main form in which the fibre is normally transported from field and can be stored next to the field for further processing. This can be re-used directly as a construction unit in straw-bale housing.
4- Hammer milled	40-100		Milling takes place after transporting the bales to the factories, and de-baling them. Main applications: paper, biocomposites and fibreboards
5- Cubed	320-640		After de-baling, manufacturing cubes takes place for animal treated foodstock or un-treated for energy applications.
6- Pelleted	560-720		After de-baling, pellets are manufactured for energy applications

Table B1-2. Different bulk density values of straw according to the physical form differences, after: (Jenkins, 1993), Photo credit: 3- bales (Sinobaler Machinery Company Limited), 5- cubes (Straw Chip Ltd, 2013) , 6- pellets: www.smallpelletmill.com, other photos: 1,2,4- researcher

Straw's application possibilities in the building industry are illustrated in the following table, according to the physical forms of straw, as follows:

Straw Applications in Architecture	Re-using of straw bales	Building with straw bales
	Recycling chopped or milled straw	Straw fibre- and particle boards
	Recycling chopped straw or straw ash	Straw bricks and cement replacement (Not included within this research)
	Recycling chopped or milled straw	Straw fibre reinforced biocomposites

Table B1-3. Straw's different applications in building industry according to its physical form variations

B 2. Building with straw bales

Through this part, conventional straw's application in the building industry through re-using the raw straw bales is illustrated. The reasons behind the limitations of method in applying straw in architecture is revealed and discussed.

Historically, straw-bale construction is relatively new as it was known for the first time in Nebraska, USA in 1880 after the development of the straw baling technique in 1870 (Unger, 2001). The straw types applied here can be rice-, wheat-, rye-, oat- straw and others.

Figure B2-1.First straw bale construction in Nebraska in 1908 (Hammer, et al., 2012)

B 2.1. Straw bale construction and international building codes

B 2.1.1. Europe

In Europe, especially in Austria, building with straw bales attracted further attention since 1995, according to BMVIT (Wimmer, et al., 2011) while in Germany, more than 80 living houses have been constructed, since 2006 when the official straw bale building construction code came into action, according to FASBA (FASBA e.V., 2013)

The interest here was to increase the percentage of renewable resources that are already present in the market of insulating materials, which are still overwhelmed by artificial fibres as renewable natural fibres are not more than 3-5% from the total amount of the insulating materials in the contemporary market, (Unger, 2001).

B 2.1.1. Asia

In Japan, India and many other Asian countries, many examples of straw bale constructions already exist. The Japanese building code does not include straw bale buildings, but inspite of this, straw bale buildings have been approved and constructed especially that rooms less than ten square meters does not require a permit in Japan (King, 2006). Straw baling construction in Asia started increasing only since the year 2000, (Vuong, 2004).

In China, the highest producer of straw worldwide, a broad questionnaire was applied in 2004 in South-China, (Vuong, 2004), to evaluate Chinese consumers' opinions on this construction type. This investigation showed that the Chinese customer is not fully convinced with the straw bale construction choice. The survey results indicated the reason for not preferring this type of construction for being primitive, in their opinion, or for needing special technical or complicated constructional methods. In the Chinese building codes, straw-bale construction is not yet included (King, 2006).

B 2.1.1. USA

The first straw bale building code was introduced in Arizona in 1996, (King, 2006). Inspite of the potentials of the baling systems' appliance in building, and even the official inclusion of the standards of baling construction, still the codes limits and restricts the number of stories in which the bales can be applied. In California's building code, one story building is limited for straw bale construction, in addition to the restricted specifications of the wall thickness: height ratio as 1: 5.6 (Sher, et al., 1995). This indicates the high commercial conflict that would occur if this constructional method is trialed in a country's city-center, where land costs are extremely high. This indicates accordingly that the realistic commercial applications of such a system should take place in rural areas of lower land costs, where the opportunity of horizontal housing-expansion exists.

B 2.1.1. North and South Africa

In North and South Africa, building with straw bales guidelines or accreditation is still not included in the official governmental building codes. In South Africa, building with straw bales are not directly approved in the building codes, but rather through the safety requirements and satisfaction rules that are related to the SABS (South African Bureau of Standards)- 0400 National Building Regulations, (Eco Design Architects and Consultants, 2013). In North Africa, namely in Egypt, attempts are still taking place to fulfill all the needed building enquiries as a step towards including the straw bales' construction systems in the local building codes, (Garas, et al., 2009).

B 2.2. Building with straw bales- Case studies

California baling codes are useful examples of the building codes regulations for building with straw, as they specify the characteristics of straw bales that can be applied as building units, whether load-bearing or not. These codes specified that the bales should be rectangular in shape, tied with polypropylene strings or metal wires, and should have a maximum inner humidity of 20%, and a minimum dry density of 112 Kg/m^3 (Sher, et al., 1995). Bales should be in rectangular to be possible to stack them over each other as a building unit. Standard bales that can be applicable for building purposes range between two common bale sizes, Width x Height: (45 or 60) x 35 cm or 40x 45 cm; while the length is variable, but normally ranges between 80-100 cm. (Straube, 2009)

The straw-bale building projects illustrated here are constructed in two different climates and regions, presenting different constructional methods, between load-bearing, non-constructional insulating filled units and prefabrication systems.

B 2.2.1. Case study- 1, Europe- Austria

Project Name: The S-House- Planning and Building for Tomorrow, Year of Construction: 2005. Architect: Mag. Georg Scheicher. Consultaion and Energy Planning: TU-Wien- Gruppe Angepasste Technologie, Dr. Robert Wimmer (bmvit- Austrian Federal Ministry for Transport,Innovation and Technology, 2005)

(a): The stacking process of the bales before plastering- (bmvit- Austrian Federal Ministry for Transport,Innovation and Technology, 2005)

(b): The finished S-House building at its final stage- (Unser Strohhaus Bau GmbH)

Figure B2-2. In S-Haus , the straw bales were applied externally as an insulating system.

In 1999, the Austrian Federal Ministry of Transport, Innovation and Technology (bmvit) launched the research and technology program 'Sustainable Development'. Within the framework of the subprogram 'Building for Tomorrow- Haus der Zukunft', the Center of Appropriate Technology (GrAT/Gruppe Angepasste Technologie) at the Vienna University of Technology developed an integrated total concept with its 'S-HOUSE' that combines many relevant aspects of sustainable building methods, (bmvit- Austrian Federal Ministry for Transport,Innovation and Technology, 2005). One of the tests within this issue regarded the fire resistance rating according to ÖNORM B3800. According to the test results, straw baling was evaluated of B2- material class (normally combustible) and the straw bale wall system tested was classified as F90. (Wimmer, et al., 2011).

This building is considered the largest straw bale construction in Austria, where straw bales are mainly applied for thermal insulation on the wooden thin frames serving as the main building hidden construction as seen in Fig. (B2-2), reaching the optimum passive construction needed with a U-value of 0,12 W/m²K for all walls, ceiling and flooring, (Wimmer, et al., 2004).

In a similar project, which was a public building for offices, shops and a restaurant, named Neubau Biohof Achleitner, financed by the same act: 'Building for Tomorrow' in Austria, the final project report's authors- in 2008- mentioned that the construction supporting system needed much higher costs than what was previously planned, due to the high weights and loads of the straw bales, (Preisack, et al., 2008), which was considered here one of the main drawbacks faced in the building with straw bales' experience.

B 2.2.2. Case Study- 2, Europe- Germany

Project Name: Passive Family House- Esslingen- in South Germany (FASBA e.V., 2013). Architect: Erz und Gugel Architekten, Year of Construction: 2008, Constructed Area: 115 m²

Prefabrication process taking place prior to straw bale filled studs installations.

Installation using a crane

The finished house

Figure B2-3. Complete process of prefabricated straw walls housing construction. (FASBA e.V., 2013)

Straw bales prefabricated systems was the construction method applied here. For rapid construction and further automization techniques in construction, straw bales were applied in wooden frames as filling insulating materials, plastered and moved to the construction plot as a packed compact unit, ready for installation, as seen in Fig. (B2-3). Passive building construction was here achieved using the straw bales for thermal insulation, in addition to planting the roofs for further insulation. The basement foundations were constructed of classic concrete and insulated by expanded polyurethane panels. The prefabricated straw bales walls, of 40 cm thickness, were then installed.

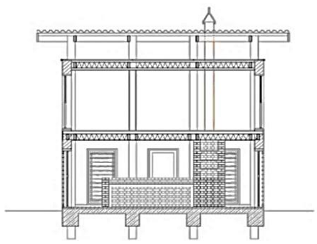
B 2.2.3. Case study-3, South Africa:

Project's Name: Ukuqala 2 – residential building (University of Stuttgart-Faculty 1-iöb- ukuquala, 2013). Architect: Students participating in the iöb seminar of WS 11/12 in the Faculty of Architecture- University of Stuttgart, Germany, South Africa , Year of Construction: 2012

(a)

(b)

(c)



(d)

Figure B2-4 . (a), (b), (c): Construction process and the final overviews of the Ukuquala-2, after construction (d): Schematic sketch of the sectional design. Photo credit: (University of Stuttgart-Faculty 1-iöb- ukuquala, 2013)

This project is one of three successive projects, built in cooperation with a number of partners including mainly a non-organizational institute that aims to help homeless children, especially those with HIV disease. The project was designed and built by 23 students under the supervision of Prof. Lederer (Institut für öffentliche Bauten und Entwerfen- iöb), Dipl.Ing. Koch and Dipl. Ing. van Gaudecker, Fig. (B2-4). The construction materials applied were local straw from South-Africa and clay based-plaster. The main construction members were made out of wood and the straw was applied as a non-constructional filling material in the form of bales. This project served as a direct method for practical architectural teaching, within a theme of 'build together-learn together'.

B 2.3. Building with straw bales: advantages and drawbacks

B 2.3.1. Advantages

Main benefits of building with straw bales are expressed in the savings in embodied energy, the thermal performance, and the cost savings. These can be shortly presented as follows:

a. Embodied energy

Embodied energy is the energy consumed to create a material, and includes different aspects and measurements, that put the material's life cycle into account. In this case, the energy applied in the manufacturing of the building material till its application phase in building industry are expressed through the following table, without putting the end-of-life phase into account.

Material	Embodied Energy (MJ/Kg)
Baled Straw	0,24
Fibreglass	30,3
Expanded Polystyrene	117
Cement	7,8
Virgin Steel	32
Recycled Steel	10,1
Virgin Aluminum	191
Recycled Aluminum	8,1

Table B2-1. Straw's embodied energy when applied as a building material, in comparison to common building materials. (Magwood, et al., 2005)

The previous illustrated values indicate that straw has the lowest embodied energy input within all other common building materials.

b. Thermal performance

The straw bale low thermal conductivity that resembles mineral wool and expanded cork, as indicated in the following table, which promotes it to compete highly within the insulation materials' contemporary market.

Material	Thermal Conductivity λ (W/mK)
Baled Straw	0,038–0,072
Mineral wool	0,035–0,045
*Expanded Polyurethane**	0,02 (@Density=30Kg/m³) – 0,04 (@Density=80Kg/m³)
Cotton	0,040
Expanded Cork	0,045–0,060
Wood Fibre	0,040–0,090
Wood	0,13
Cement	2,1
Steel	50
Aluminum	160

Table B2-2. Thermal conductivity comparison between straw bales and other conventional synthetic and natural insulation building materials. *: (FAO, 1989). Other Info: (Holzmann, et al., 2012)

c. Cost savings

According to cost analysis, occurred by (Garas, et al., 2009), cost savings can reach up-till 40% when building with straw bales. This is due to the cheap raw materials cost and energy savings. Price stability of straw promotes it to highly compete within the conventional artificial insulation materials, when applied for insulation. In the following figure, straw bales of 35 cm that has the same insulation properties of a 25 cm- mineral insulation and a 25 cm- fossil-based insulation, has shown stagnant prices within 11 years as seen between the years: 1997-2008, which contradicts the other two materials' cases.

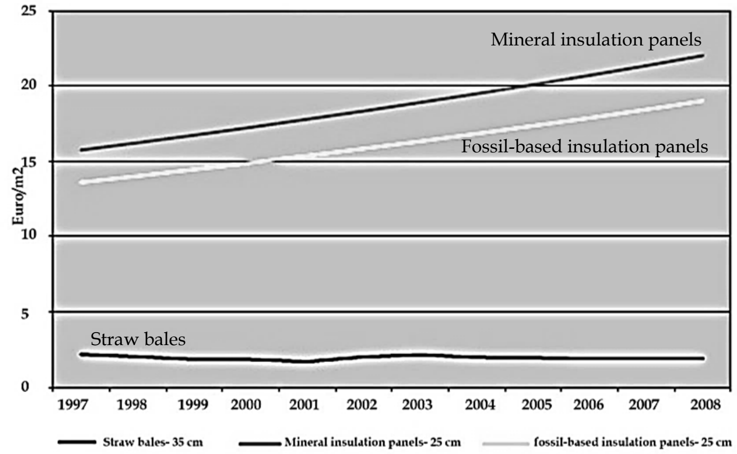


Figure B2-5.Price comparison between straw bales and conventional insulation materials. 1997-2008 (Wimmer, et al., 2011)

B 2.3.2. Drawbacks

a. Appearance

The brown un-attractive appearance still appears as a main aesthetic drawback to the customers worldwide. The un-awareness of the straw potentials and the customers' ideas of dealing with straw bales as a primitive material that lack much design options, are one of the reasons behind the limitation of straw bale building applications; as illustrated by (Vuong, 2004).

b. Thick walls' dimensions

This consumes large space areas, because of the large bales' widths. That makes this system not practical to be applied in cities' centers, where land costs are too high, and vertical housing densification is the popular applied building method. Cost savings would be lost in this case, since the land-price will count much more in the final cost of the building, than the building materials' costs.

c. Installation and quality control difficulties

Within the construction phase, manual straw bales' handling and installment is of much higher difficulty in comparison with conventional bricks, because of their relative high weights. Many solutions were established in this aspect, using prefabrication methods for straw installations, then installing the walls using cranes afterwards in the sites (FASBA e.V., 2013), as previously illustrated in one of the case studies.

In addition, straw bales need a high-value control system unit, which can follow the flow of the bales from the field to the storing units, then to the customers. The quality of the bale itself, its inner humidity and wrapping method as well as the wrapping-wire's material are also of important aspects, when the bale is directly applied in the building industry. However, natural fibre-quality control problems exist in almost all other industrial natural fibres' types, as in the case of hemp and flax for instance.

d. Building codes and regulations

The contemporary international building codes consist of classical and identical building methods, which do not directly apply with straw bale building (Searle, 2011). Straw bale construction needs further developed methods of construction, that are still not matching the available conventional constructional regulations worldwide, which leads many engineering consultants not to go further with this construction method, to avoid troublesome extra testing, that is mostly needed for a new straw-bale building's permit, which is another negative cost value in this case.

B 2.3. Conclusions and development suggestions

- As building with straw bales started spreading in Europe during the last decade, it was indicated by (Unger, 2001) and (Wimmer, et al., 2011), that the lack of acceptance and low readiness for innovations hinder the commercial use of straw as a building-material. He indicated that the practical experience exchange and the providing of well-established prefabricated systems, would lead in this case a big straw market in the near future that can compete with natural cellulose. Inspite of the previous interpretation, building with straw bales has proven itself more in Europe and North America than the rest of the world, Fig. (B2-6). Although the straw amounts are much highly available in Asia, users are still not encouraged to adopt such a successful, available and cheaper method for local applications. This was clearly declared in the social investigation illustrated by (Vuong, 2004) that showed the non-preference of the majority of the users to such a construction method. In Africa and South America, the situation did not differ. This can be clearly revealed through the following figure:

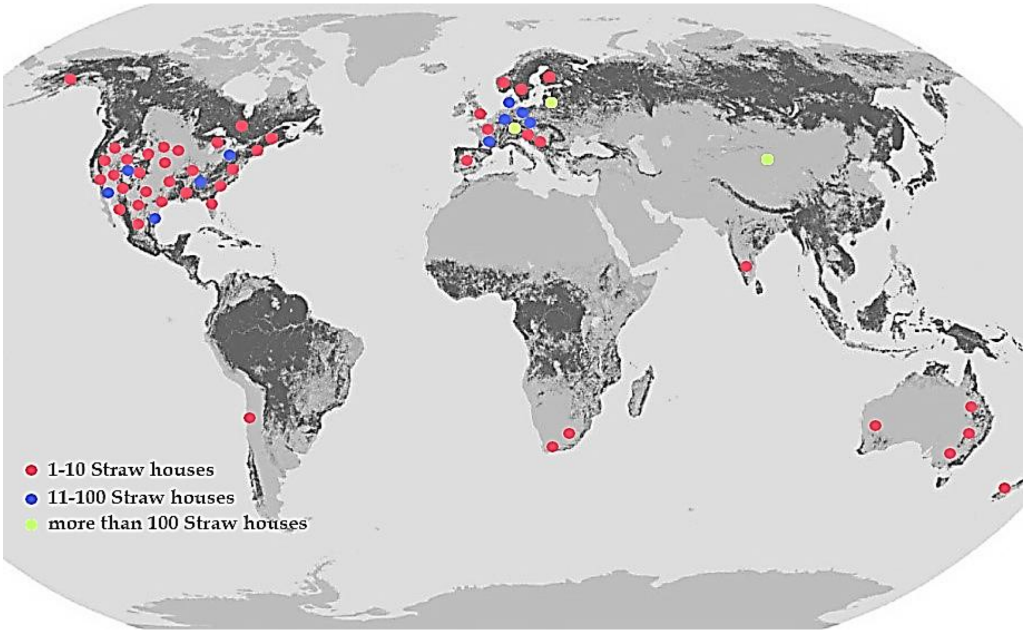


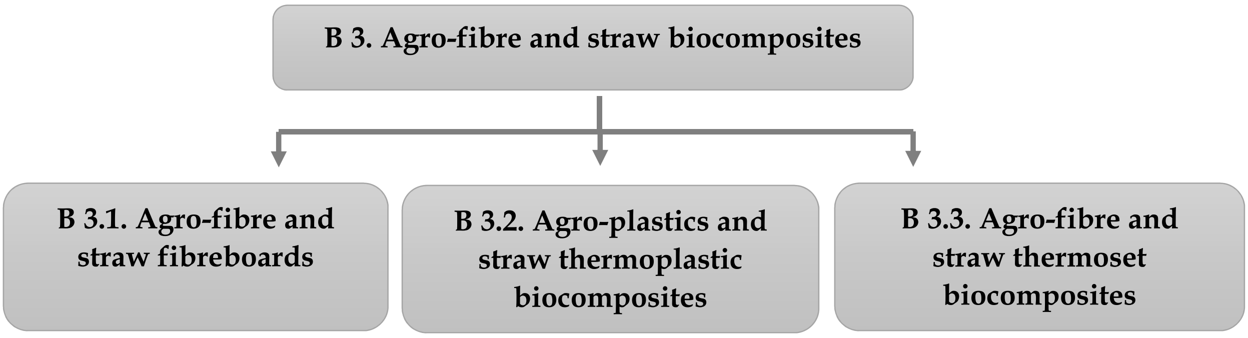
Figure B2-6.The distribution of straw-bale constructions worldwide and in different climatic zones, re-illustrated after (Wimmer, et al., 2004). Map photo credit: FAO, 2006

Accordingly, if straw baling seems un-attractive for a lot of users worldwide, then applying straw as a raw material for colored straw fibreboards and biocomposites is another possible option. Moldable straw biocomposites can be an attractive alternative to spread straw as a renewable raw material and fibre-resource in the contemporary building market. Putting into consideration the special chemical composition of straw and its natural flame resistance, promotes the importance of making use of straw as an effective eco-filler in biocomposites, which is what is applied in this research. This should highlight the importance of straw as a main component of biocomposites that can be mainly applied in the building industry, instead of the classic straw bales with its low aesthetic and technical drawbacks.

Through the following part, the state of art of the previous agro-fibres and straw biocomposites' researches are illustrated.

B 3. Agro-fibre and straw biocomposites

In this part, the state of art of the main three selected forms of agro-fibre biocomposites is separately illustrated. This part is divided into three main sub-divisions as follows:



B 3.1. Agro-fibre and straw fibreboards

Currently composite boards refer mostly to the wood adhesive bonded products ranging from fibreboards to laminated beams, composite molded products and others. (Arias, 2008)

For the sake of wood replacement, it was suggested after the changes in practices of forestry, (McNutt, et al., 1992), since almost a century to apply agro-fibres as a main component in fibreboards. Agro-fibres in this case are mostly bonded using thermoset resins, to form fibreboards. Straw's geometry after milling is considered of much positive advantages than wood, as it is more slender than cubic; hence leads to uniform surfaces and acceptable mechanical properties within particleboards, MDFs or flooring substrates in comparison to wood composites (Wasylciw, et al., 1998).

The methods of fibreboards' manufacturing are generally divided into two main production methods:

a. The wet fibreboards' manufacturing method:

This is an extension to the paper industry, where the fibre distribution occurs in water as the fibrils are distributed in a mat form, before being pressed as a board, and the fibre moisture content during production exceeds 20%. In case of high temperature appliance within this process, the fibres slip apart and the lignin matrix between the fibres is softened, and consequently, mostly no extra binders are applied as the softened lignin would serves as an adhesive in this case, (Berglund, et al., 2005). For the wet process, the fibreboards with a density ≥ 0.9 g/cm^3 are considered hardboards (HB), while boards with a density ≥ 0.4 g/cm^3 to <0.9 g/cm^3 are considered Medium density fibreboards (MDF), (Halvarsson, 2010).

b. The dry fibreboards' manufacturing method:

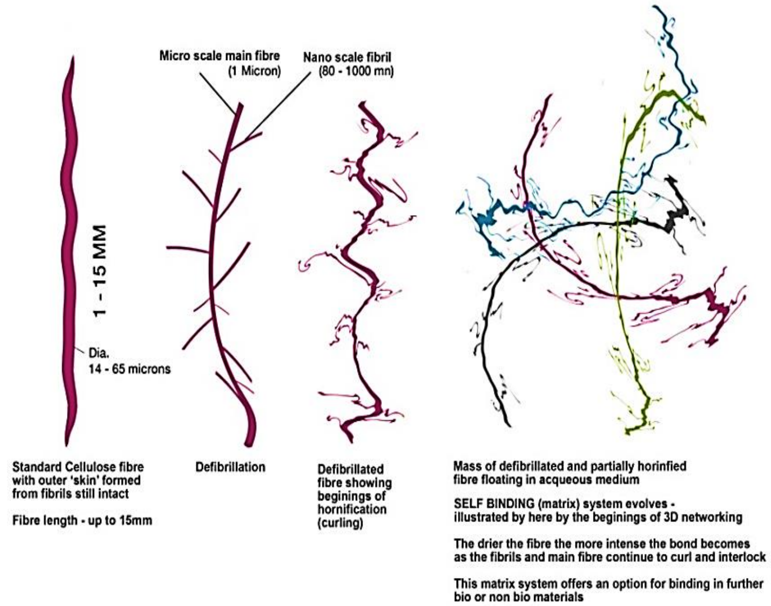
This is considered a more environmental friendly process, where fibre's moisture content should be less than 20%, and fibre distribution takes place using air blow where fibrils are fed from a dryer to be bonded with a binder, before being web formed, then pressed into a fibreboard, (Berglund, et al., 2005).The binding process takes place conventionally using a synthetic resin in small quantities under hot pressing's application. For the dry process, the MDF is considered when its density lies between 0.5 - 0.8 g/cm³, the HDF (High density fibreboard) when density ≥ 0.8 g/cm³, while low weight fibreboards (low-density fibreboards) are with a density of ≤ 0.4 g/cm³, (Kulshreshtha & Vasile, 2002) . Particleboards is considered one of the fibre-boards forms, but processed mainly using a dry process using a resin under heat and pressure, achieving low board densities. (Arias, 2008)

B 3.1.1. Wet agro-fibreboards manufacturing

Straw binderless boards' production depend mainly on the old known process of non-resin fibreboards' manufacturing , which is a wet process, where the lingo-cellulosic fibres are generated through steam explosion that softens fibres' lignin, and through hot pressing, the lignin contributes to the final formation of the boards. The main disadvantages of such a process are the high water consumption, dark color of the boards and long pressing times. This is nowadays mostly converted to the dry process applying low resin percentages to bond the fibres by hot pressing. It is not easy to produce non-resin boards that can serve exactly as the commercial resin-boards and fulfill their requirements. This was indicated through (Halvarsson, 2010), in a direct approach towards production of straw-based MDF fibreboards, where his developed non-resin straw MDF fibreboards did not fulfill the MDF standards, EN standard for MDF (EN 622-5,2006).

The manufacturing process is usually not only accompanied by heat and pressing, but mostly by applying chemical treatment to activate the fibres' surface to increase the level of bonding, in addition to additives and resins' appliance for better water-resistance as well as physical and mechanical properties, (Mobarak, et al., 1975). For less thickness swelling, waxes and linseed oil have been applied on the rice straw pulp; which improved water resistance, but highly decreased the board strength. In other researches, applying thermal treatment improved both water resistance and mechanical properties of straw-based fibreboards whether with or without applying extra resin (Fadl, et al., 1983).

One of the successful contemporary wet fibreboards' production technologies without binders' appliance or chemical treatment, but rather mechanical refining process for the agro-fibres, was achieved by the Zelfo® process owned by the international Zelfo Technology GmbH. This technology depended on refining the agro-fibres to obtain microfibrils in a wet process where the fibrils are hornified (i.e. referring to the physical change of the fiber upon drying, (Minor, 1994)) and bound through natural hydrogen bonding, Fig. (B3-1) (Hurding, R., 2012). This process is patented and illustrated within the patent, (Robert, et al., 1998), that the special physical methods applied on the fibres causes the fibres' surface enlargement through fibres' grinding and refinement to take place, within an aqueous microfibre pulp followed by a molding and drying process. The resulted densities can be low or medium, lying between 0.4 to 0.9 g/cm³, that can be mainly applied for heat and sound insulation, or high till 1.5 g/cm³ that can be applied for structural applications with insulation properties, (Zelfo Technology GmbH, 2014). The only drawback of this process is the high energy cost, applied in the drying process of the fibreboard.



„Cellulose Optimization Resource Efficient (CORE)“ technology, making use of the lingo-cellulose resource from agro-residues' resources. Published after permission from R.Hurding- Zelfo Technology GmbH

Samples from the produced medium to high density fibre plates from agro-fibres. Foto credit: Nova Institut (up), Zelfo GmBH (down)

Cotton bush-the agricultural by-product after cotton harvesting, transferred into an insulating board using 'CORE' technology. Published after permission from R.Hurding- Zelfo Technology GmBH

Figure B3-1. Illustration of the de-fibrillation technology applied to produce binder-less boards of agro-fibres with high technical quality, known as Zelfo® technology

B 3.1.2. Dry agro-fibreboards' manufacturing with different matrices

a. MDI and UF matrices

Polyisocyanates- the main component of the (MDI) was found in the early 1970s to be capable of bonding straw fibres than the classic commercial urea formaledyde (UF) that is commercially applied with wood, as the MDI could penetrate the straw surface layer than the later one, (Groner, et al., 1972). However, MDI is more expensive than UF and at the same time should be applied with higher quantities to achieve the same UF binding effect, (Wasylciw, et al., 1998).

Within boards' manufacturing, when thermoset resins like isocyanates are applied, it is necessary to keep the straw fibres relatively humid, ranging between (8-15%), after fibre refining to be able to wet the fibres properly with the matrix, before being hot pressed at 400-800 psi at around 200 °C. (Yang, et al., 2006).

b. Bio-based soy-protein adhesives

On the other hand, many approaches occurred to apply much more environmentally-friendly adhesives within straw- and agro-fibreboards' making, including the application of modified soy-protein, which was successful and caused comparable technical properties with the agro-residues' fibreboards from classic fossil-based binders, (Zhong, et al., 2002), (Mo, et al., 2001).

c. Cereal wastes-based adhesives

Other trials revealed the possibility of preparing cereal wastes' based adhesives, where adhesives can be derived from the agro-fibres themselves, then combined by the same cereal wastes' fibre's species or other agro-fibres types. This was revealed in the patent of (Zhongli Pan, 2005), who successfully prepared an adhesive from the rice bran, which is the combination of the layers lying between the white rice seed and the external rice husk/hull which is normally removed within the rice milling process and considered a by-product. Protein adhesives derived from this rice bran was prepared and applied to combine the lingo-cellulosic fibres to form agro-fibreboards.

d. Bio-based tannin adhesives

One of the existing approaches of producing eco-friendly constructional fibreboards based on agro-residues' fibres and bio-based tannin-based adhesives, Fig. (B3-2), was distinguished by a common project between Nigeria and Switzerland. The green agro-fibre based boards were manufactured to be applied in the building sector with affordable prices in Nigeria that suffers from housing problems, as an impact of the building materials' high costs, (Job, et al., 2011).

Different agro-fibres' types, between husks and corn cubs — *Natural agro-fibres' crushing procedures*

Applying mechanical tests — *Final Agro-fibre products*

Figure B3-2. Illustration of the agro-fibre- tannin biocomposites, (Job, et al., 2011)

e. Non-organic matrices- gips, plaster and cement binders

Attempts of combining straw with other inorganic binders like gips/plaster, (Slotter, 1952) , and cement took place for insulation boards' production. It was found that specially with cement, bonding and dehydration were of many difficulties due to the high moisture percentage, that only functioned by adding an accelerator like calcium chloride, (Cong, et al., 2006). Straw cement blocks were also tested and applied, still in lab scale, for structural applications accompanied by thermal insulation efficiency, (Mansour, et al., 2007), or for non-load bearing application possibilities and mainly for thermal insulation performance (Akmal, et al., 2011).

f. Elastic binders

Attempts to manufacture fibreboards using recyclable binders exist rarely within the dry fibreboards manufacturing methods worldwide. In the international contemporary building markets, no agro-fibreboards with elastic or recyclable binders still exist. However, wood fibre particleboard with an elastic binder do exist in the European market, under the name of Recoflex® from (BSW Berleburger Schaumstoffwerk GmbH). The elastic wood fibreboard is also combined with cork through an elastic binder to achieve less weight and better acoustical performance.

Previous researchers tried applying straw fibre in a lab-scale with different elastomeric binder types, like synthetic rubber, (Fujimoto M., 1988), or recycled waste tires for acoustical insulation as well, but the fibres' filling-ratio by weight was as low as 30%, (HS, et al., 2004).

g. Binder-less cartoon-wrapped fibreboards

One of the known agricultural compressed fibreboard technologies worldwide is called Stramit technology, which was a patent that started in Sweden since 1933, according to (Ortech Industries Pty Ltd) , depending on compressing untreated straw fibres for high temperatures of around 150°C to produce mainly non-structural roof and wall insulating boards, after being encased in thick cartoon layers, that are covered by fire- and water-resistant layers, (Aero Research Limited: Technical Service Department, 1952), (Englert, 1980). Since then, it was further developed with different production techniques and was spread and applied worldwide. In Germany, examples of these straw panels' types exist in the contemporary market with the commercial trade names: strawtec® , (Strawtec Group AG) , and istraw®, (Technisches Vertriebsbüro Burgstaller) . This cartoon-wrapping procedure provides the rigidity needed, and waives away the disadvantages of the binderless boards to a great extent, which are mainly expressed in the fibres' flying-out from the board's core.

Most of the insulation materials currently present in the market are dominated by mineral wool, fossil-based extruded and expanded polystyrene, as well as fossil-based polyurethane, forming together around 93% in 2011, (MarketsandMarkets, 2012) . Other insulating materials with small quantities of renewable resourced boards do not exceed 3-5%, (Unger, 2001).

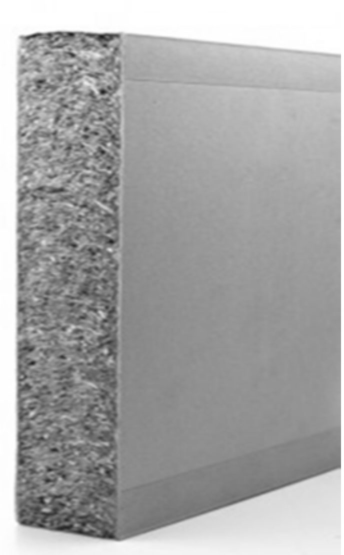


Figure B3-3. Straw cartoon panel, where straw is pressed and packed in cartoon paper,Photo: Joachim Stumpp (MaterialBlog, 2013)

Figure B3-4. Straw cartoon panels fixation possibilities on hidden stud boards, (Technisches Vertriebsbüro Burgstaller).

Figure B3-5.Mensch-Haus-Umwelt office building with straw panel walls, wrapped in cardboard-strawtec® (Strawtec Group AG)

B 3.1.3. Straw fibreboards technical performance in comparison to wood fibreboards and other agro-fibres

Generally, straw fibreboards' properties were acceptable according to the European standards, (Troger, et al., 1988). According to (Wasylciw, et al., 1998), the straw's appliance instead of wood in fibreboards' making, resulted in equal if not better mechanical properties than that of the wood-based fibreboard panels.

In investigations achieved by (Halvarsson, 2010), rice straw MDF boards were developed from defibrillated and chemically-modified fibres after applying MDI and UF resins separately at 3-5% wt. loads, to reach average densities between 0,65-1,1 g/cm^3. The researcher here defined that the acceptable internal bond (IB) of a typical MDF, which is the strength measured in the board thickness direction, is in the range of 0.55 – 1.20 MPa. He was able to reach through his investigations, a high IB value of 2,6 MPa for his developed high density rice straw-MDF of a 1,06 g/cm^3 recorded density.

In other researchers, it was revealed that other agro-fibres like cotton stalks and bagasse were found better in performance in their fibreboards' mechanical properties than that of rice straw fibreboards, applying the same processing technique and binder type. (Fahmy, et al., 1974)

As a conclusion, it is clear that inspite of the differences in straw fibreboards' performances, as recorded in some cases, in comparison to wood and other agro-fibres, it still fits within the limits prescribed within the official standards of fibreboards' requirements worldwide.

B 3.1.4. Global agro-fibreboards manufacturing

Through the following a quick global view for agro-fibreboards' investigations is reviewed as follows, after (Youngquist, et al., 1996):

- In both Africa and North America and attempts from China, (Jingxing, 1988) and India, (Shuala, et al., 1986), revealed that straw and *bagasse* (i.e. the agro-by product resulted from the sugar cane, after extracting the sugar from it) were applied in fibreboards making.
- In North America, rice straw was more applied as complete straw bale building units, as discussed, than as a main raw material for fibreboards, in comparison with Europe and Australia, (Stramit USA, 2012).
- In the Middle East, including Egypt, rice straw and bagasse were applied as main components of fibreboards' production. Rice straw fibreboards of good mechanical properties were reached especially using appropriate fibrillation techniques, (Fadl, et al., 1984).
- In Europe, many researchers studied straw for fibreboards' production especially in Germany, (Hesch, 1978), (Troger, et al., 1988), while in Sweden, bagasse has been found as an ideal alternative to wood in fibreboards' manufacturing, after the dramatical increase in the local wood prices.
- In the area of the former Soviet Union, rice straw has been applied in fibreboards' making using steam and ammonia chemical treatment, which resulted in achieving good mechanical properties and minimum thickness swelling, (Kluge, et al., 1978).
- In the Philippines, other available agro-by products like coconut shell fibres (coir) and banana stalks were more applied in fibreboards' manufacturing, than other agro-fibres (Youngquist, et al., 1996).

B 3.1.5. Advantages and drawbacks of the current straw and agro-fibreboards

a. Advantages

a-1. Economic and ecologic advantages

Due to the increase of the global wood prices worldwide accompanied by deforestation's spreading, straw and agro-fibre's appliance can highly compete in the local markets replacing wood in the boards' manufacturing and applications. However, technical challenges still exist due to the wax surface of the straw, which prohibits the bonding with conventional cheap resins.

a-2. Insulation and fire resistance performance

Straw fibreboards can play a vital role when applied in sheathings, doors' cores and room partitions for their high thermal and acoustic insulation performances. According to strawtec® - an available straw-cartoon board in the German and European market, (Strawtec Group AG), panels of 6 cm and 14,5 cm thickness can insulate sounds till 32db and 49db with F30 and F90 fire resistance rates respectively.

b. Drawbacks

b-1. Water absorption/ thickness swelling:

The water resistance and dimension stability of agro-fibre MDFs are complicated to manage and control. Accordingly, to overcome this, many researchers suggested chemical and/or thermal fibre modification, oil and waxes appliance, compatible adhesives appliance and thermal fabrication processing (Fadl, et al., 1983).

The critical water resistance properties are regulated in DIN EN 622-5, which regulates the technical requirements of the dry manufactured fibreboards. According to this standard, fibreboards' thickness lying between 1.8-2.5 mm have accepted thickness swelling until 45% for boards that will be applied in dry conditions

In (Halvarsson, 2010), straw fibreboards combined with resins between 3-5% had a high swelling ratio ranging from 15-30%, inspite of the chemical additives, defibrillation and thermal treatment. This is due to the lower lignin amounts, higher hemicelluloses components that lead to more hygroscopic characteristics that caused an increase in water absorption, hence swelling, (Sun, 2010).

b-2. Synthetic resins' appliance: ecologic evaluation

Most of the available commercial resins applied in the contemporary fibreboards' manufacturing consist of formaldehydes as a main component like urea formaldehyde (UF) or phenol formaldehyde (PF). This is still a huge environmental and health problem, due to the diseases that can be caused by inhalation of these substances when they are applied in interiors, as continuously tiny amounts of the resin evaporates in the inner air at room temperatures, known as volatile organic compounds (VOC). This is considered a big threat for human health. In case of formaldehydes, it is classified as a very volatile organic compound (VVOC) as it evaporates at 19.5°C, which makes it the most dangerous and health-risk material ever spread nowadays in our buildings, especially through fibreboards. (Holzmann, et al., 2012 p. 32).

Although isocyanate, the main component of the commercial resin methylene diphenyl diisocyanate (MDI), is considered a non-formaldehyde resin, it is considered a cancer-cause one and accordingly has been classified as "R 40 category 3 carcinogen" since December 2010 by the European Union. (Holzmann, et al., 2012 p. 35).

The harmful problems resulting from applying such dangerous adhesives do not only appear during the useful life-time of the boards, but even after the end of their life-time, since appropriate incineration would be very expensive, and even recycling or down-cycling, will not be possible. So, the destruction affects humans, living organisms and the whole eco-system.

B 3.1.6. Conclusion-suggested development

In this research, rice straw will be combined with an elastic binder to manufacture high density straw fibreboards with an elastic nature and a high fibre ratio of 80% by weight. This kind of fibreboards can cover a wide range of applications in architecture that is not yet covered by the conventional dry-based fibreboards that depends mostly on non-recyclable thermoset binders. This developed straw fibreboard would have many advantages including recyclability and free-form geometries' achievements, using appropriate price-wise fibreboards, due to the high fibre-filling percentage, that is still rarely available in the markets. Development of the rice straw fibreboard will be discussed in Chapter C, and the applications in Chapter D.

B 3.2. Agro-plastics and straw thermoplastic biocomposites

In this part agro-fibres' compounding advantages with bioplastics is highly emphasized, discussing the previous researches and available products in the contemporary building markets of green agroplastics.

B 3.2.1. Fossil-based plastics and bioplastics:

a. Fossil-based plastics

Fossil-based plastic industry ranks the third among all other industries worldwide. Plastics' applications in building industry in Europe forms the second largest plastic market after the packaging industry, which is around 20.5%of the total plastic usages in different industries, of which the PVC ranks the highest consumed type, then PE-HD, PS-E, PUR and PP respectively afterwards, according to Plastics-Europe in 2012, (PlasticsEurope AISBL, 2012). Globally, plastics perform around 29% from the total chemicals applied in construction (Plank, 2005).

b. Bioplastics

Bioplastics is a newly emerged type of plastics, that is either biomass-based plastic or biodegradable fossil-based plastic according to the European Bioplastics e.V. definition. Accordingly bioplastics include bio-based biodegradable plastics like PLA, lignin and starch blends; as well as bio-based non-biodegradable plastics like PLA blends, Bio-PP and Bio-PA; in addition to fossil-based biodegradable plastics like PVA, PBS and PCL. Being biodegradable or compostable is emphasized according to the DIN EN 13432; regardless of being derived from a biomass-basis or a fossil-basis.

Bioplastics emerged within the 1980s, depending on the concept of having degradable plastics that would offer another disposal option depending on biodegradability, (Endres, et al., 2013). The applications were since then mostly directed towards the products' types of short life-time including grocery bags, agricultural applications and many others. This concept however have elaborated with time, even after technologically manipulating the degradability option to the fossil-based plastics and achieving this extra disposal option from fossil-based plastics as well. Nowadays, the interest in replacing the non-renewable fossil-plastic resources with bio-plastics based on renewable resources is extremely increasing, especially if the bioplastics produced were meant to be resistant for longer life-times. This is due to the advantages of bio-plastics over fossil-ones including being of self-renewing resource base, and incorporating less energy-input within production, since nature has already taken over a part of the synthetic input, hence possessing less or no carbon footprints.

On the market perspective, both compostable and fossil -based bioplastics, as well as resistant bio-based bioplastics are available. The dominant bioplastics types available in 2013 are the resistant-bio-based types, that can be applied in construction and automobile industries; which are in need of more persistent materials, out of more natural basis for better consumers' health, especially in interior rooms like in building interiors and in car salons.

The total bioplastics production amount is still less than 1% of the total plastic production worldwide, however the increase in the annual growth in production is at least 20 %, according to the European Bioplastics e.V.

Concerning land use for this 1% plastic production, an area of about 5000 km ² of agricultural land would be required in the year 2015 for the global Bioplastics' production, which represents only 0.03 % of the world. In theoretical consideration, only approximately 5 % of the global agricultural land would enable bio-based plastics to replace all petroleum-based plastics worldwide, Fig. (B3-6), (Endres, et al., 2013). Inspite of all these mentioned facts, it is still ethically, socially and politically worldwide required to replace the foodstock by the lignocellulosic resources, won from the agricultural by-products in specific to form the so-named "second generation biopolymers" and biocomposites accordingly, (Carus, et al., 2011), as declared in Fig.(B3-7), since agricultural residues fibres form a lignocellulosic resource from which natural fibres as well as polymers can be extracted and synthesized respectively, Fig. (B3-8).

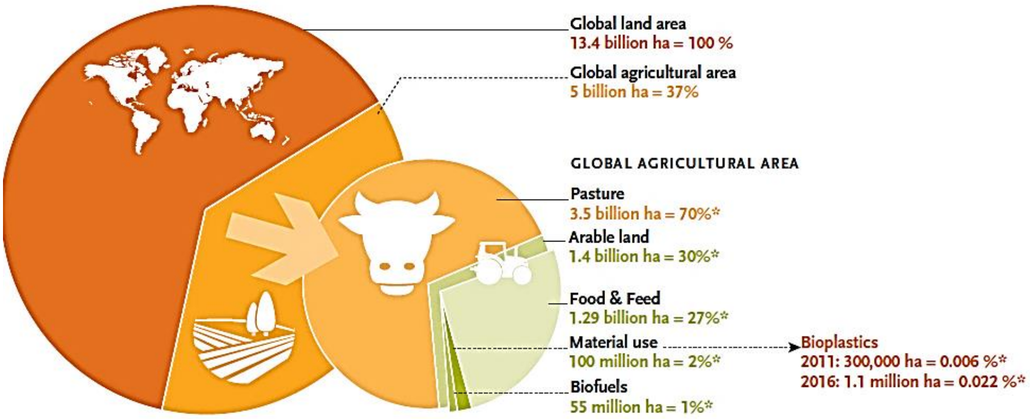


Figure B3-6. Global land use for bioplastics in 2011 and estimated in 2016, after European Bioplastics e.V., IfBB in October 2012 and FAO, (european bioplastics e.V., 2013 S. 10)

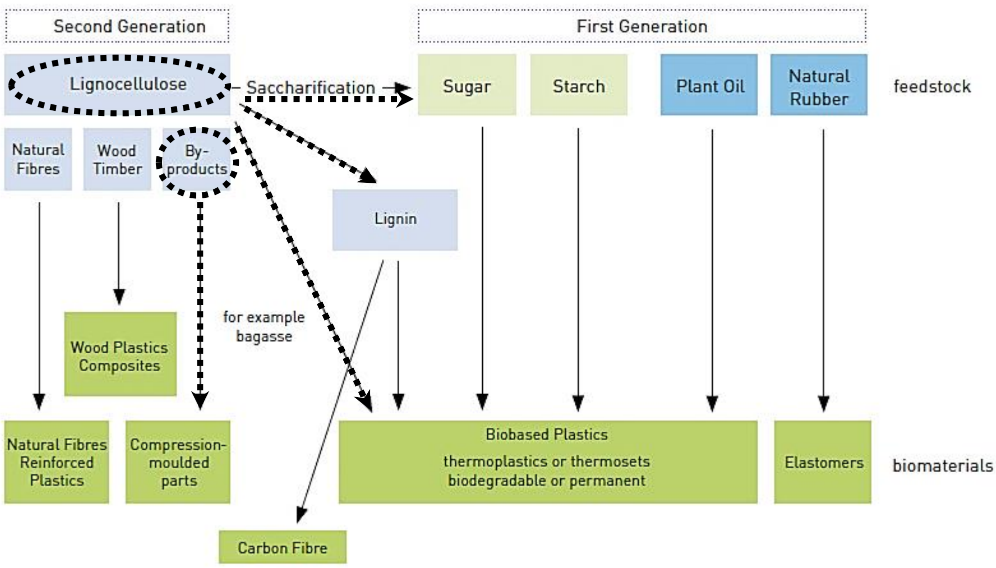


Figure B3-7. Illustration of the second generation supply of the "new" generation of the near future biopolymers and green biocomposites from agricultural by-products including straw, bagasse, ..etc, after nova-institut, (Carus, et al., 2011)

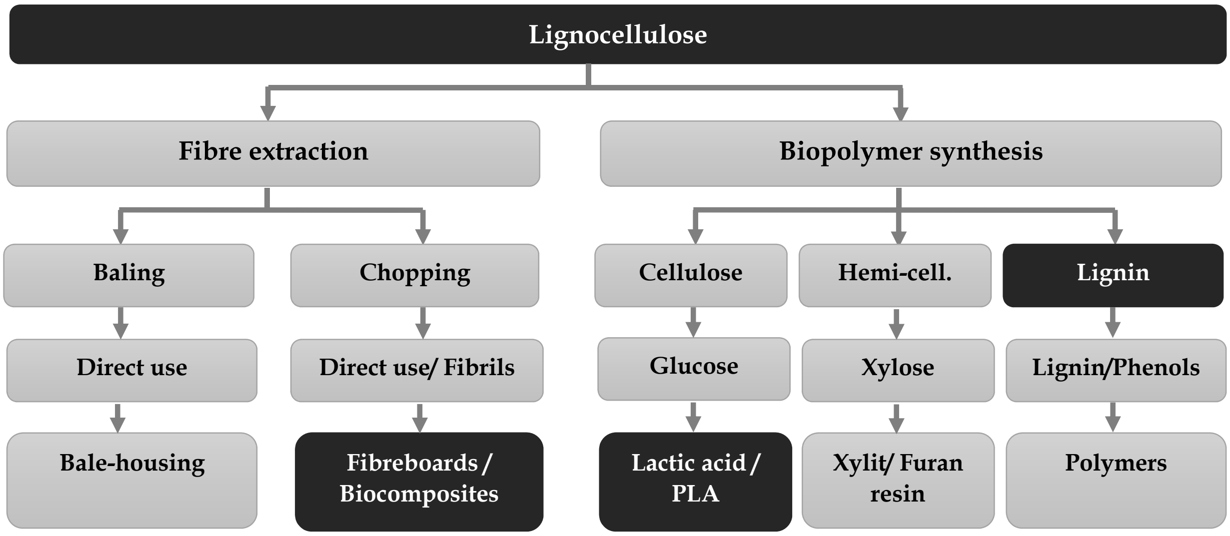


Figure B3-8. Lignocellulose biomass as a source of natural fibres and biopolymers. ***Polymer synthesis: after*** (Hirth, T.- Fraunhofer IGB, 2012 S. 72)***; Fibre extraction: researcher.***

As illustrated, depending on the main components of the lingo-cellulosic fibres, fibres could be extracted and applied as a main biocomposite ingredient as here tackled throughout the research; and bio-polymers could be as well extracted as indicated through the figures, where glucose derived from cellulose could be transformed to lactic acid, and accordingly to PLA synthesis. Similarly, lignin can be extracted to formulate the lignin binder, as applied afterwards in this research, or through hemicellulose extraction that can be transformed into a resin. Accordingly, the PLA and lignin bioplastics applied in this research within the developed green rice straw thermoplastic biocomposites, can be themselves derived from the rice straw fibre, as described.

An example on this second generation of biopolymers is the launch of the third plant of Natureworks LLC company, the biggest PLA producer worldwide depending on corn stover and other plant residues, according to (Shen, et al., 2009). It is stated as well in this report, that parallely, PURAC company (Gorinchem, Netherlands), the largest natural lactic acids' and lactates' producer worldwide, launched new plants depending on abundant Tapioca starch in Thailand since 2007, which is another evidence of the reason that makes Asian countries the highest possible candidate to overwhelm the bioplastics and green biocomposites accordingly starting from now and in the near future, as stated later in Table (B3-1).

Regarding bioplastics' prices in respect to fossil-based plastics process, the gap between both is decreasing with time, after (Endres, 2012 p. 100), Fig. (B3-9), while on the other hand fossil-based plastics' prices are growing continuously with time, Fig. (B3-10). As seen, PLA as one of the dominating bioplastics in the contemporary market, competing with the common conventional PP and PET.

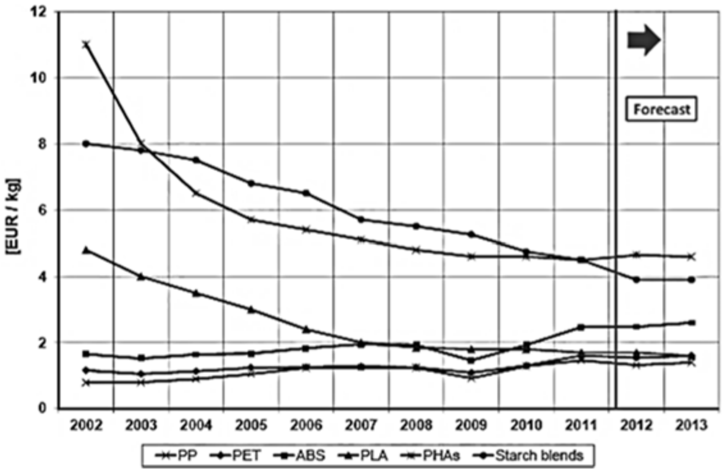


Figure B3-9. Current prices of common dominating biopolymers in the market in comparison with fossil-based plastics, (Endres, 2012 p. 100)

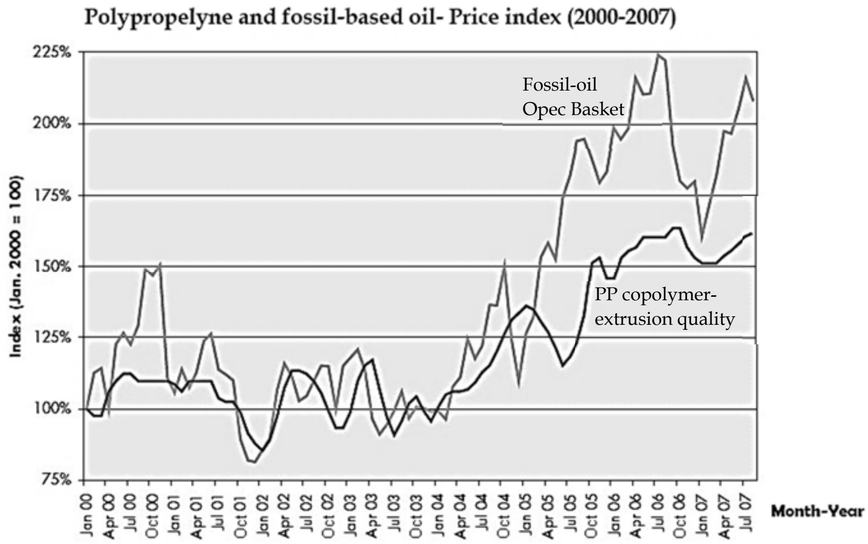


Figure B3-10. Illustration of the continual increase of petro-based oil and plastics' prices since 2000-2007, after Kunststoff Information Verlagsgesellschaft GmbH, reproduced from nova-Institut, (Carus, et al., 2008 S. 301)

Through the following table, Table (B3-1), a comparative analysis of the global biopolymers' contemporary and future production is indicated.

2012: Biopolymers Production Capacity in (%), Total= 1.274 Mt					2016: Biopolymers Production Capacity in (%), Total= 5.778 Mt				
Europe	Asia	N.America	S.America	Australia	**Europe**	Asia	N.America	S.America	Australia
17.2	38.8	12.9	30.7	0.4	**4.9**	46.3	3.5	45.1	0.2

Table B3-1. Biopolymers production capacity sorted after regions, for the years 2010 and 2015. ***Information adapted from IfBB,*** **(IfBB- Statistics, 2013).**

As illustrated, Europe's role in biopolymers' production capacity as well as materials' share capacity are shrinking, after IfBB, (IfBB- Statistics, 2013), while Asia and South America would be the most suitable plots for the near future green agro-fibres biocomposites applications, due to the presence of the abundant lignocellulosic resources, that can be applicable for both fibre and biopolymer productions.

According to (IfBB- Statistics, 2013), packaging industries and bottles' manufacturing as well as electronics and agricultural applications are the main contemporary and near future expected applications for bioplastics. However, it is hereby highlighted the advantages of applying bioplastics in the building and architectural fields, in the form of green biocomposites, considering construction and demolition wastes' amounts worldwide, and how these types of composites would supply safer end-of-life disposal options than the available conventional ones. Therefore, it would be a successful option to combine the advantages of the agro-fibres, and those of bioplastics, as here suggested and applied.

B 3.2.2. Biocomposites and green biocomposites

Biocomposites is a term that describes the combination of two components, a fibre and a matrix, where at least one of them is a biomass-based component. When the two components are biomass-based, then the biocomposite is considered a green biocomposite, as illustrated in the following figure. Green rice straw thermoplastic and thermoset biocomposites' development is one of the main targets of this research.

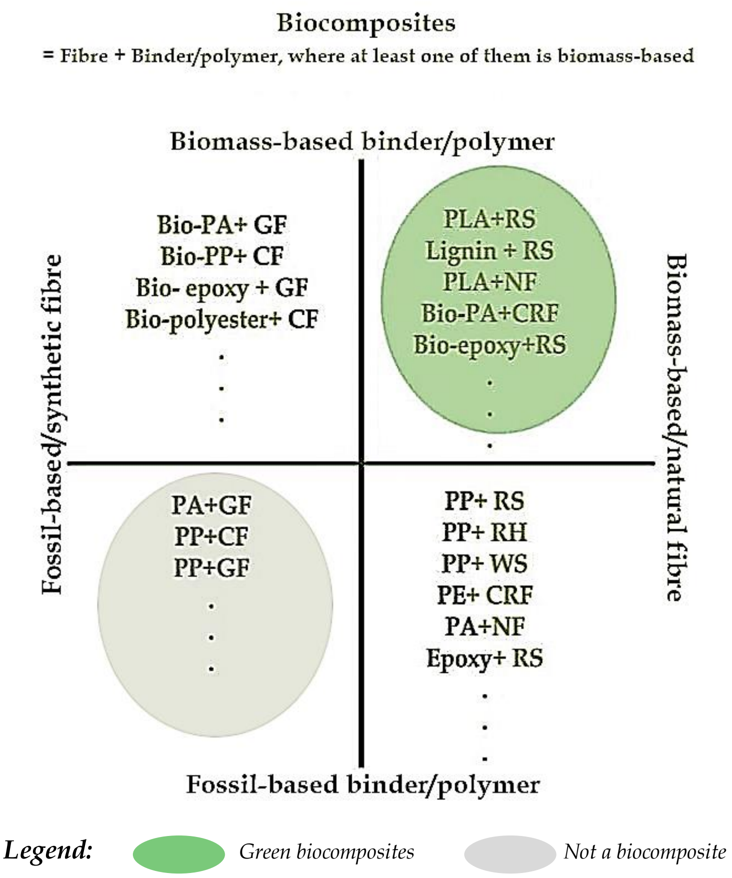


Figure B3-11. Sketch illustrating biocomposites' basic types, illustrating the main research concern (Green Biocomposites). Biocomposites illustration is derived after Endres, H.-J.; IfBB , (Endres, 2012).

B 3.2.3. Natural fibre reinforced biocomposites and natural fibre filled biocomposites

Within biocomposites, the natural fibre is either applied to provide extra rigidity to the whole composite that is not achievable with the polymer or matrix alone; hence called natural fibre reinforced composite, or applied to replace and reduce the amount of polymer applied-being an active eco-filler, and hence called natural fibre filled composite. The differences depend on the fibre-length and the reason behind adding the fibre in the composite. For short free-oriented fibres, no mechanical improvement would be expected when added to the polymer, since no reinforcement would take place; but rather an ecologic as well as an economic effect should take place in the final biocomposite product since this fibre is cheap, which is the main reason for choosing it in the first place. A change in the technical properties would take place as well when this filler is of special characteristics that would interact with the binder/polymer not through reinforcing it, but through its own chemical and other physical properties. These last mentioned reasons of natural fibre filled composite's appliance, are the ones behind applying the cereal straw in this research. As a scientific term, natural fibre reinforced composites covers both scopes of reinforced and filled composites. Accordingly, NFRC (natural fibre reinforced composites) is the common term applied, even when a NF- filled composite is meant. WPCs is a famous example on this. When WPCs started evolving since 1997, wood flour was applied as a filling agent to decrease the cost, through replacing the plastic binder applied, "*but was not usually intended to improve the performance in any substantial way*" as indicated by (Mohanty, et al., 2005 S. 7). In the same sense, straw fibre is applied to replace the binder/polymer for economic reason, with another advantage that is not available in wood-fibre, which is the natural flame-retardant silica contents.

a. WPC (Wood plastic composites)

One of the successful and wide applications of natural fibres with plastics is the WPC which started in Europe as a leader in this industry since the end of 1990s, then was dominated afterwards in the USA since the year 2000 uptill now, (Vogt, et al., 2005). WPCs appeared historically much earlier in the form of milled wood filled thermosets before the 1960s, and started appearing in its known wood plastic composite form, only in the 1990s, (Klyosov, 2007 S. 78-79). The chopped or milled wood fibre can be mixed uptill 90% by weight to plastics, (Carus, et al., 2007 S. 157), which are normally PP or PE (Poly-olefins) or PVCs, however the typical wood plastic product is a mixture of 70% wt of wood flour with 5% additives for compatibility as bonding agents, in addition to UV-protection additives as well as pigments, which are all added to the 25% plastic, (Vogt, et al., 2005).

In many commercial WPC products, lingo-cellulosic fillers range from 35-60% only, depending on the mark-type and the required properties. WPC is not limited to wood lingo-cellulosic filler's appliance, but rather a wide range of natural fibres' appliance possibilities, including agro-fibres of which rice-hulls/husk present the highest applied type within this category, in the form of ground fibres, (Klyosov, 2007 S. 75-77).

The combination of the high lignin-filled wood dust together with other flammable plastics, like polyolefins, increase the critical situation of WPCs future appliances in buildings, due to the new fire-resistance regulations set worldwide. Solving this through classic mineral additives, should be theoretically possible, as Klyosov describes in his book, but in this case the final price will highly increase, which is already around two-three times the normal wood price, and the WPC will turn into a mineral-filled plastic instead of wood-fibre filled one. Most of the WPCs lie in the material category 'C' of FSI (flame spread index) lying between 76-200, in comparison to normal wood that has a FSI ranging from 100-200. WPCs combination with low-flammable plastics like PVCs, results in WPCs of lower FSI of range 25-60., (Klyosov, 2007 S. 10,11,36). However, PVCs appliance is still environmentally criticized.

In automotives industry, inspite of preferring NFCs for their high technical properties, there's a huge drawback to their appliance due to their high cost, in comparison to WPCs, Fig. (B3-12). This high cost is due to the different procedures in which the natural fibres should go through, for optimization before being compounded, especially that the applied fibres in this case are those expensive natural fibres obtained from fibre crops like flax, hemp, sisal and jute.

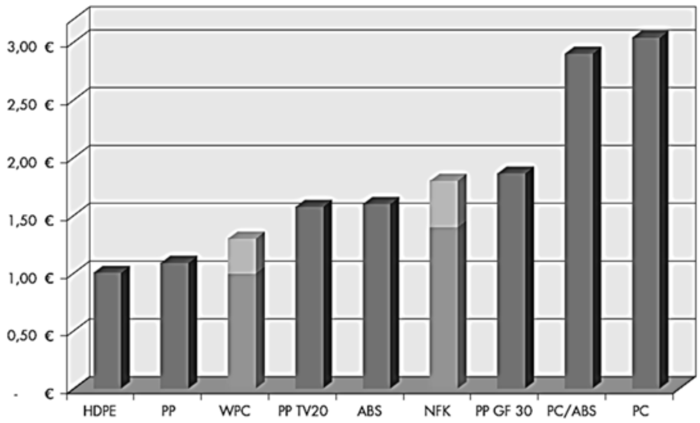


Figure B3-12. Illustration of the WPC and NFK (NFC) average prices differences in automotive industry in comparison to typical conventional plastics in 2006, according to Nova Institute (nova-Institut, M-Base, HS Bremen, SSP, 2007)

b. Agro-plastics replacing WPC and NFC

A lot of investigations took place in respect to agro-fibres compounded with fossil-based plastics (i.e. agro-plastics) whether in Europe, North America or Asia, resulting in products that resemble WPCs (wood plastic composites) in physical and mechanical properties, providing the high optical, free-design possibilities and the ability to be colored and molded in different geometries according to the desired consumer requirements. This helped in replacing WPCs through the newly evolved agro-plastics in the contemporary building markets.

Replacing wood and other industrial natural fibres became of a big interest in many fibre-based industries, mainly for economic reasons. One of the clear examples of this is the replacement of hemp, that was once applied in 1941 through straw fibres in 2010, in new Ford automotives. Hemp, flax, ramie and cork were applied in the famous hemp-Ford automotives when combined with soya-wool and plastics in 1915-1941, which was the first famous industrial example of the NFRC in history. In the year 2010, a big project for car bodies out of straw-PP biocomposites was launched, under the name of Fordflex, (Starke, C.; Magnani, M.; Fanzen, M.- Ford Forschungszentrum

Aachen, 2012 pp. 240-244), Fig. (B3-13). It is therefore highly expected in the near future the effect on this action on other industries including architectural and building industries, just as the historical mutual effects between the industries regarding new materials' technologies.

In the contemporary building markets, a number of agro-plastics' trades, based on agro-fibres and fossil-based plastics, already exist and applied in the building sector. On the other hand, no green agro-plastics exist on an industrial scale, till the time of writing these lines.

Photo credit: http://hemmings.com

Photo credit: http://techcrunch.com

FUTURE

A car made from hemp- Ford- 1941 **Ford's using wheat straw in a 2010 Flex component**

Figure B3-13. Illustration of the future expectation of straw appliance in biocomposites applications

c. Agro-plastics processing possibilities

Biocomposite's processing technique depend mainly on the type of binder applied and the physical form of the natural fibre.

The common compounding process takes place through the extrusion process by heating the thermoplastic polymer whether externally or through the mechanical shearing of the inner screw(s). Such processing is limited to the short fibres' compounding, which is the expected length that can be gained from most of the agricultural residues' resources, especially bast-based ones. Long and continuous fibres are mostly not applied. In recent researches however, this became of high interest and started on lab-scales. The heating temperature should be carefully applied and not to exceed a certain limit (around 190-200 Degrees),(Pott, 2004 p. 118), so as not to cause fibre rapid decomposition. This would lead to failure in the compounding process and /or un-satisfactory composite performance.

After compounding, the composite can be either directly extruded into a final product through a mould that should be fit in the machine in this case; or can be pelletized and packed for a reprocessing procedure through further extrusion or injection in a separate process. In other types of plant natural fibres gained from fibre crops, as in the case of flax, hemp, kenaf and cotton, other compounding methods can be applicable as the fibres in this case are long enough to produce yarns and fabrics, then comingling processes are possible. The composites in this case are finalized through hot pressing so that the polymer would diffuse within the fibres, resulting in a high performance fibre composite.

In case of agricultural residues' bast fibres, straw fleece and mats' making are also options for forming textile-wise forms of the agro-fibres that can optimize their application varieties. But till the moment, these types of agro-fibres' physical form do not exist in industrial scales for biocomposites' industrial applications. The commercial agro-residual fibres biocomposites depend mainly on short fibre processing techniques, including extrusion and molding. Foaming techniques for short natural fibres' polymeric composites were also found possible on lab-scale, (Bergeret, et al., 2011).

After processing, the thermoplastic biocomposite products are finished through lamination or drilling to give the product its final design and attractive touches that can make the product then competitive enough in markets. This aspect is important in all industrial applications, especially in architectural ones. Throughout this research, examples of green straw-biocomposites that can fit into architectural applications will be illustrated, and the final finishing of the semi-finished product through laser cutting or thermoforming will be discussed.

B 3.2.4. Agro-plastics – Previous developments- Review:

a. Agro-fibres with PVC:

Straw-PVC biocomposite with a fibre load of 20% by weight was developed, but in a solution form after treating the straw fibres chemically and applying bagasse lignin as a coupling agent. The results depended greatly on the PVC and lignin concentrations as well as the pressing time and temperature that was raised till 200°C for 20min. to gain high mechanical properties, (Kamel, 2004).

b. Agro-fibres with polyolefines:

Within the common available natural fibre/plastic technology, the typical fibre load by weight is around 40%, 50%PP and 5%compatibilizer, according to (FNR).

In a patent by (Zeiszler, 1995), sugar beet pulp and (virgin and/or recycled) polyolefines were compounded to produce colored structural composites for decking and door slabs and window frames applications, with 50% of fibre load by weight or volume, that can be increased uptill 98%. The composite was achieved after applying extra stabilizers and modifiers to the composite.

(Yao, et al., 2008) and (Yao, 2008) compounded different untreated agro-fibres including rice husk (RH), Straw leaf (SL), Straw stem (SS) and whole rice straw fibre (RS), at different fibre loads (30%) and (50%) with virgin and recycled high density polyelthylene (HDPE) separately, then compared the results with wood fibre (WF). It was recorded that the fibre source within the rice straw, whether applied as a whole in biocomposites' production or separating leaves or nodes and applying them individually, will not have a big effect on the mechanical properties of the final product, which is an advantage that would enable the direct appliance of rice straw in industry without complications of straw parts' separation prior to compounding. The results have shown that the mechanical properties of RS is comparative with WF, which indicates the possibility of applying RS instead of wood in thermoplastics, especially with polyolefines. He indicated that the mechanical properties decreased with the fibre load increase as the fibres were not modified and additives or compatibilizers were not applied.

To achieve higher mechanical properties without fibre modification, compatibilizers should be applied, based on previous researches, (Habibi, et al., 2008), (Sombatsompop, et al., 2005), as this affect positively the technical properties, causing improvement in the tensile and flexural strength, but probable decrease in the compact strength.

The applied compatibilizers would be maleic anhydride (MA) grafted PE and PP (PE-g-MA or PP-g-MA), upon previous researches done applying the same technology with wood fibres to activate the polar interaction and the covalent link between anhydride carbonyl of the compatibilizer and hydroxyl groups of the fibre surfaces, (Kazayawoko, et al., 1999), in addition to being compatible with the polyolefin matrix, (Lai, et al., 2003), (Lu, et al., 2005). On the other hand, polyolefinic elastomers were also applied as compatibilizers to improve the impact strength of the natural fibre/polyolefine composite, which was not successful alone as an additive, but gave better results in combining both compatibilizers' types, or by preserving good control on the applied ratios so as not to increase than certain levels so that mechanical properties will not deteriorate. Tensile strength can be increased by 19% at 1.5%PE-g-MA in comparison with pure HDPE; and improved with further increase of PE-g-MA load (4.5%), uptill 38% tensile strength improvement than the virgin polymer, (Yao, 2008). Generally maelicanhyhdride was always evaluated, uptill the moment, as the most successful compatibilizer within short free-oriented natural fibre thermoplastic biocomposites regarding polyolefin matrices.

c. Agro-fibres with bioplastics (Green agroplastics)

c.1- Rice straw-PHB

Rice straw was also applied as an effective filler in green biocomposites on lab-scales by (Buzarovska, et al., 2008), combined by poly (hydroxybutyrate-co-hydroxyvalerate) (PHBV), the biodegradable biopolymer. RS was applied in 2 load ratios, 20% and 30% by weight without previous treatment or compatibilizers' addition. Accordingly, the mechanical properties were negatively affected (tensile strength decreased) due to the poor fibre/matrix adhesion. Further future investigations were accordingly suggested.

c-2. Rice Straw (RS) - PLA

RS-PLA was developed and its properties were compared with glass fibres-PLA, within the framework of ECO-PCCM project, supported by the EU FP6-INCO program. It was concluded that RS can successfully replace the artificial fibre as well as wood fibres in collaboration with the biodegradable polymer in similar applications, (Avella, et al., 2009).

Another study was applied in Austria, through the TU-Wien Team within the "Fabrik der Zukunft" Programm, which was launched in the year 2000, through which many local raw plant materials were investigated, specifically cereal straw. Through this project, a fleece was developed out of a homogenous mixture of straw, and other local natural fibres including flax and hemp, then smoothed and lined up with PLA biodegradable bioplastics' threads, in addition to PHB particles as well as chemically modified starch binders, (Wimmer, et al., 2007).

The straw and flax reached around 70% wt., while PLA was around 30%wt. The fleece was successfully produced through sheet-forming process, then was thermo-pressed into plates and forms, that were successfully colored and applied in variable forms, Table (B3-2). The planar boards manufactured were applied in the straw bale house "S-House", which was previously described in the last part of this chapter, as interior non-structural partitions.

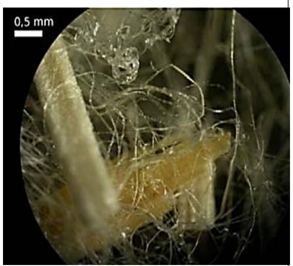
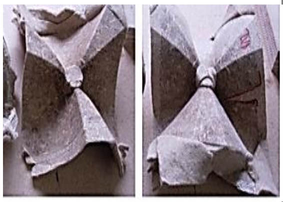
1- Fibre Preparation	2-Fleece Making	3-Thermo-pressing	4-Released Products	
			Planar Pressed Partitions	3D natural and colored/laminate d products
   Straw mixing stages with other fibres	  Non-woven fleece fabric after the thermal treatment	  Pressing at 180°C for 5 minutes	 Partition in the S-House out of the pressed developed fleece	 Car-interior trim  Bag's body  Laminated pressed forms-household and packaging

Table B3-2. Illustration of the straw-flax/PLA fleece making, and the outcome products reached within the "Fabrik der Zukunft" Project, Austria, (Wimmer, et al., 2007).

c-3. Rice Husk-PLA

Rice Husk (RH) was applied, accompanied by the conventional coupling agent maleic anhydride (MA) with the typical ratio (5%) with grafted PLA, and the examination revealed the possibility of applying the rice husk as an effective eco-filler as well, (Srebrenkoska, et al., 2009).

c-4. Agro-fibres- Lignin

It has been reported by (Mohanty, et al., 2012), how the disposal and the value of lignin should be further considered for a better economy and environmental sustainability. Within this aspect, the patent team studied the lignin's blend with poly (butylene succinate) (PBS), which was important to enhance the thermoplastic activity of the purchased lignin biopolymer, then incorporating the blend to a mixture of chopped switchgrass and miscanthus agro-residues fibres. They found that adding only 1% of PMDI, a novel compatibilizer to the lignin-PBS mixture, was capable of increasing the mechanical properties of the green composite produced extensively. They set the developed material to products in interior automotives' industry, especially for car door panels.

Otherwise, limited investigations were recorded for agro-fibre-lignin biocomposites. In most of the researches, lignin has been mostly applied as a nucleating agent in blending processes for other polymers to improve their properties. This was recorded by Weihua et al. who applied lignin to improve the thermal properties of lignin-polyhydroxy butyrate (PHB) composites, (Weihua, et al., 2004). Lignin-polymer blends including lignin-based polyurethane, lignin-based epoxy composites, lignin-rubber composites and lignin thermoplastic composites have been reviewed by (Kumar, et al., 2009).They stated as well the possibility of phenol replacement in phenol-formaldehyde formulations, and in polyurethanes by lignin. In addition, it was applied as an adhesion promoter or compatibilizer within biocomposites, including PVC-RS as previously mentioned in, (Kamel, 2004). Lignin was also applied as a coupling agent within PLA-cotton biocomposite development by (Graupner, 2005), and a compatibilizer as well in jute fabric-PP composites, (Acha, et al., 2009), where its incorporation improved the PP-jute adhesion. It was also reported through the applying lignin to the wood flour based polycaprolactone (PCL) ,to obtain a cost-effective biodegradable composite, based on bio-based and fossil-based resources, (Raquez, et al., 2008) .

B 3.2.5. Agro-fibres and straw thermoplastic biocomposites- Market availability

Most of the available agroplastic products in the market are composed of agro-fibres combined with fossil-based conventional PP, PE and PVC polymers. From these commercial products are:

a. Wheat Straw (WS) and recycled (HDPE):

Different market products are based on agroplastics, including TerraFence™, TerraDeck™ and TerraWeave™ that are composed of wheat straw and recycled plastics (HDPE), (Natures Composites TM- organic building products, 2011), Figs. (B3-14, B3-15). The company's plant and facilities are located in Torrington, Wyoming- in the centre of USA, where the wheat straw used to produce the lumber-resembling products is grown by regional farmers and a large percentage of the recycled plastic used in the manufacturing process is sourced from the Rocky Mountain region, which is also in the surrounding area. Hence, the resources are guaranteed from nearby plots with the needed continuous supply for the industry. The applications of the same developed material include fences and decking as previously declared, in addition to flooring. The materials suits external applications and are applied for structural and heavy duty needs.

Figure B3-14.TerraDeck™ of recycled HDPE and straw, (Natures Composites TM- organic building products, 2011).

Figure B3-15.TerraWeave™ of recycled HDPE and straw,forming 3D-formed screen, (Natures Composites TM- organic building products, 2011).

b. Rice Husk (RH) and PVC

- This thermoplastic biocomposites is made of rice husk components up till 60% by weight, PVC and mineral oils, which is present under the name of Resysta® in the contemporary building markets, (Resysta International GmbH). This product is more expensive than wood, but can replace it in heavy duties' applications and providing free-form geometrical curvatures in furniture and 3D fittings, (Dorfer, 2010). The German-investors have located their company in Malaysia next to the rice hull-supply. The furniture company, based on the same developed material lies also in the nearby, in Indonesia-Asia.

Figure B3-16. Resysta® being applied in a building façade by the Asian architect:Nguyen Lam Dien in Vietnam, (Resysta International GmbH).

- Another agro-fibre thermoplastic biocomposite, under the name of Ricycled™ is also applied in the building industry. The company which is owned by British investors is also settled in Malaysia, for the same reason so as to be next to the raw material supply. The agroplastic is composed of RH, that is grinded to powder then also compounded with PVC (recycled), which is obtained from pipe factories and credit card factories, Fig.(B3-17), (Ingram, H.; Denby, S.- Ricycled Asia Pacific Sdn Bhd). The fibre load reaches 55% by weight, (Denby, 2011), and the developed material is suitable for external and heavy duty applications including decking, fences, flooring, dunnage and gluts replacing classic wooden ones as well as window frames and doors.

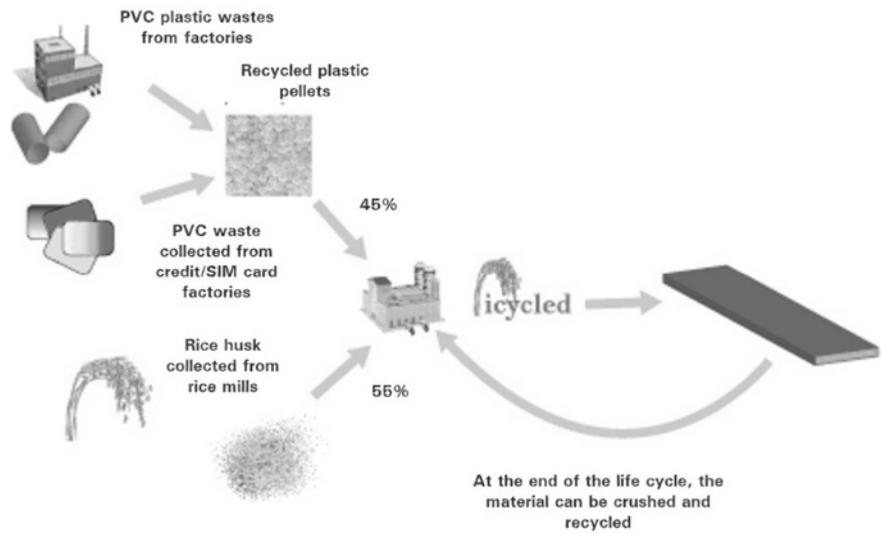


Figure B3-17. Illustration of the product life cycle of Ricycled™ according to Ricycled Asia Pacific SdnBhd, (Ingram, H.; Denby, S.- Ricycled Asia Pacific Sdn Bhd).

As previously discussed, no green agroplastics exist in the contemporary markets. On the other hand, industrial natural fibres-bioplastics compositions do exist in the new materials markets, but not yet for architectural applications, but rather for electronics' bodies, household items and others. In the following part, these green natural fibre thermoplastic biocomposites are illustrated with PLA and lignin, with an illustration of the proposed suggestion within this research of developing green biocomposites from agro-fibres with the same discussed bioplastics types and to direct them for architectural applications, which is the main target of the research.

B 3.2.6. Natural fibres with PLA and Lignin- Market availability

a. Kenaf and hemp with PLA

a.1- Kenaf-PLA

Kenaf-PLA was applied to manufacture mobile phones' coverings and laptops' cases, with a 15%wt. fibre load, through the Japanese companies UNITIKA and NEC Corp. in 2006, (Goda, et al., 2008 p. 341), as well as inner applications as spare tires' covers in automotives from Kenaf-PLA for TOYOTA in 2003.

a.2- Hemp-PLA

Musical instruments' bags were produced from Hemp-PLA, with around 50%wt. fibre load, through the German company Frenzel und Jakob Winter GmBH in 2006 as well.

Another application from Hemp-PLA, in the form of urn was produced by Linotech GmBH in Germany, (nova-Institut, M-Base, HS Bremen, SSP, 2007), (me'o Consulting Team, Faserinstitut Bremen, nova-Institut GmBH, 2007 p. 25).

Within the following table, Table (B3-3), the mentioned market products of NF-PLA are illustrated, accompanied by the proposed objective of the research for the developed RS-PLA, which will be reviewed within the coming chapters.

Kenaf- PLA		Hemp- PLA		RS- PLA
				*Interior Architectural Designs and Applications*
UNITIKA,NEC Corp.and NTTDoCoMo. Photo: © Paul Fowler , TOYOTA		*Frenzel und Jakob Winter GmbH, Linotech GmbH*		*Details in Chapter D*

Table B3-3. Illustration of a number of products ' designs in different applications from NF-PLA green biocomposites, proposing the suggestion of the research of RS-PLA for architectural applications, applied in chapter D

b. Cotton and hemp cellulose with lignin

The only available serving product in the market that is based on lignin as a thermoplastic biopolymer combined by natural plant fibres, which is known as liquid wood , is "Arboform®", which is produced by the German company Tecnaro GmbH, that is a spin off the Fraunhofer Institute –ICT in Karlsruhe, Germany.

Within this research, green RS-lignin biocomposite is developed. In the following table, examples of the existing green NF-lignin biocomposite products are illustrated, accompanied by the proposed idea and scope of application of the RS-lignin composite developed in this research.

hemp/cellulose-Lignin (Arboform®)			RS - Lignin
			*Interior Architectural Designs and Applications*
Tecnaro GmbH (Boards, Gucci® shoe, sound system)			*Details in Chapter D*

Table B3-4. Illustration of a number of products' designs in different applications from NF-Lignin green biocomposites, proposing the suggestion of the research of RS-Lignin for architectural applications, applied in chapter D

B 3.2.7. Advantages of green agroplastics

a. Economic Value

The value of adding the cheap fibre economically was the main reason behind applying this technology worldwide, especially after the evolution of the domination of the plastic applications in many fields including building industry, (Johnson, et al., 1997).

According to the authors, the return on investment for a 15-ton/day agroplastic plant is almost 2.7 times doubled when the fibre load of straw increased from 30%wt. to 50%

wt., where the total investment return changed from 6,5% in case of 30%wt. to reach 17,5% when straw's filling load reached 50%wt.

b. Ecological value

End-of-life options

Applying straw fibres to the bioplastics would guarantee more options for the materials' recovery in positive manners back to the environment.

These options include recycling, composting through bio-degrading turning nutrients back to the soil, or incineration in safe-guarded conditions for energy recovery through different WTE (waste-to-energy) technologies, giving back the same carbon dioxide amounts once absorbed by the plants before their harvest, meaning CO2-neutral green energy, after (Endres, et al., 2011).

Accordingly green agroplastics would enable the reduction of carbon footprints represented in the greenhouse gas emissions, Fig. (B3-18).

Figure B3-18. Illustrative sketch of the end-of-life options of agroplastics. Credit of logos' photos: www.dddigitalcolour.com, www.vaiwai.com, www.supgroup.com

Energy efficiency and CO_2 foot-print reduction

- For biobased resistant bioplastics, and evolved resistant green agroplastics cascading benefits at the end of their useful life-time phase due to their both materialistic and energetic benefits. This is due to the possibility of recycling the resistant bioplastic to a number of cycles, then still having the possibility to be fed into the regular waste stream of waste incineration plant for energy recycling. In this case, this type of energy supply after making use of the bio-based products for a specific life time, is much more resource-efficient than the direct burning of the bio-based fuels for energy uses, without any materialistic applications before the energetic ones, according to the Renewable Energy Sources Act (EEG), after (Endres, et al., 2013).
- Agro-fibres have minimum or no CO_2 footprint, since minimal energy is consumed to produce them. On the other hand, bioplastics - the second main component of the green agroplastic biocomposites - have much less environmental load than the fossil-based plastics, as indicated in Fig. (B3-19)

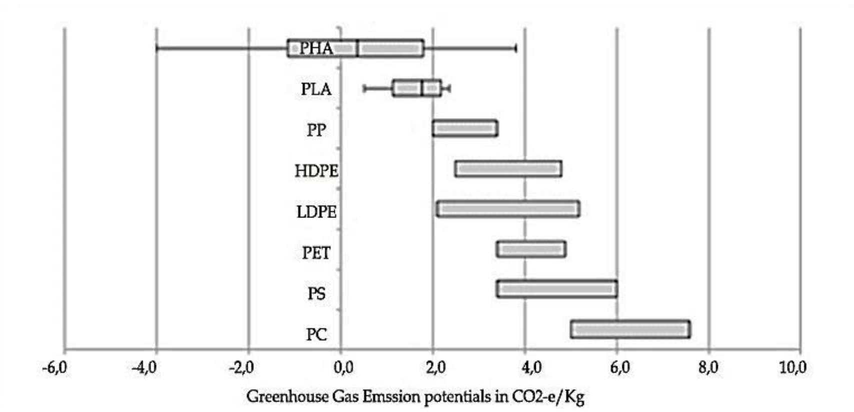


Figure B3-19. Illustration of the greenhouse gas formation amounts within the manufacturing of fossil-based plastics in comparison to bioplastics manufactured from plant-derived resources, (Endres, 2012 p. 120) .

B 3.2.8. Conclusion- suggested development

Through the previous discussions and the clarified advantages of green agroplastics, further agro-plastics' developments will take place throughout the following chapter. In this context, rice straw will be bonded in its raw chopped form with 20%wt. with PLA and lignin bioplastics, without compatibilizers' appliance. The effect of the natural existing silica in the rice straw on the final developed green RS-thermoplastic biocomposites will be evaluated especially regarding their flammability behavior. In addition, the possible architectural applications of these materials will be illustrated accordingly.

B 3.3. Agro-fibre and straw thermoset biocomposites

Agro-fibre thermoset biocomposites form another important application possibility of agro-fibres in architecture, offering new design options as well as other important economic aspects, decreasing the overall costs of similar materials, produced out of pure fossil-based resins, especially for external applications, as well as for obtaining complex free-form designs, whether for interior or exterior applications.

In this approach, green thermoset biocomposites is one of the main targets to achieve in this research through combining the selected agro-fibre with bioresins, which is the biomass-based equivalent to the fossil-based conventional resins (organic thermoset polymers). Within the following a quick review of fossil-based and bio-based resins (bioresins) is illustrated.

B 3.3.1. Fossil-based resins and Bioresins

a. Fossil-based resins

Fossil-based resins refer to the commodity synthetic fossil-based thermoset polymers. The main types include fossil-based -epoxies, -polyesters, -phenols, -polyurethanes and others. The resin is normally composed of 2 main components, that react chemically when mixed according to specified proportions that differ according to the resin type and to the resin's production method. The mixtures may set in different temperatures and may require extra pressure to solidify.

In this research, bioresins are the ones with the highest concern, due to its biomass-origin that would form much more ecologic material outcome when combined with the selected natural fibres, than that when combined with conventional fossil-based ones. Within the following part, bioresins description is thoroughly indicated.

b. Bioresins

Bioresins include natural resins and biomass-derived resins. Natural resins are much older and known than the synthesized biomass-derived ones. The biomass-derived resins that are meant here are the ones derived from the rapid-renewable plant resources.

Natural resins were generally derived from animal bones, skins and plant-oils, natural rubbers,…etc, and exist already long before the nowadays known artificial resins whether synthesized from a fossil-based origin or derived from a plant-oil one.

From the famous types of naturally-existing bio-resins is waxes, especially bee-waxes, and shellac which is a natural resin secreted from the female lac bug on special trees in the forests of India and Thailand.

From the natural sources of resins, of which bio-resins can be synthesized, according to the Building Research Establishment Ltd. include: Tannins, Lignins, Cashew Nut Shell Liquid (CNSL), Carbohydrates, Triglycerides, Proteins, Bioalkyds and Waxes, (Jones, D.; BRE, 2007). As previously discussed, lignin which is a natural thermoset existing resin, can be modified in a special process through plasticizers to act and to be processed as a bio-thermoplastic matrix, hence discussed in the previous part as a thermoplastic and not as a thermoset resin.

Vegetable oil based resins is the modern alternative possible trend to replace fossil-oil based resins as illustrated by (Petrović, et al., 2004). They declared that the vegetable oils are composed of multiple esters of fatty acids and glycerin, i.e. triglycerides, where those fatty acids aren't totally saturated, causing the oil to be liquid, although fats are solid at room temperature. This is due to the slow-reactive double bonds present in those fatty acids, which are needed to be activated to be applicable in oil-based coatings and resins' industry that can be applied to form the biocomposites, as here meant. In this case, different solutions could be offered through introducing functional groups, to make the resin reactive, that should include hydroxyl, carboxyl, amine or epoxy groups which activate the resin through their presence in the position of the double bonds. For epoxidized vegetable oils, the internal epoxy groups would be still less reactive than the primary epoxy groups and would mostly need elevated temperatures to cure, as will be seen within the application of the PTP® resin in the first developed green RS-thermoset biocomposite in the next chapter.

However in some case, the cross-linking could be reached in room temperature after introducing the appropriate strong activation through both the reactive agent in the resin itself in addition to the hardener, as trialed in the second green RS biocomposite manufactured within this research, presented as well in the coming chapter, using Gripox® resin.

Many other attempts took place to produce bio-based resins, based on plant-oils and natural fats, including polyurethane resin that was partially developed from natural oils and fats, (Poltrock, 1997), and other bio-based polyurethane resin types from the company Cognis Deutschland GmbH, which was also derived from plant-oils and fats, (Skwiercz, 1999). However, these commercial bio-resin types still contained high amounts of petro-chemical components, (Müssig, 2001).

For vegetable oil based resins' manufacturing, it was found that polyurethanes –PU resins' curing can be easily controlled and curing time can be reduced to very short times, hence reaching high economic values, by shortening the composite's production route, (Petrović, et al., 2004).

Commercially, the four main present bio-resins in markets, after (Fowler, et al., 2007), are: an epoxidised soybean oil acrylate that serves as an UV-curable coating and named 'Ebecryl 860' supported from UCB Company. The second one is the previously mentioned PTP®, that is later applied with straw in the coming part of this chapter, which is manufactured by Biocomposites and More GmbH, the formerly named company PREFPRM Polymerwerkstoff GmbH, who manufactured the bioresin PTP® from linseed triglycerides and polycarboxylic acid anhydrides. A third example of bio-resins is called 'Tribest S531' which is a triglyceride acrylate, manufactured by Cognis Company through a ring opening technology of an epoxidized triglyceride through acrylic acid. Cara plastics company/University of Delaware produced as well an epoxidized soybean oil.

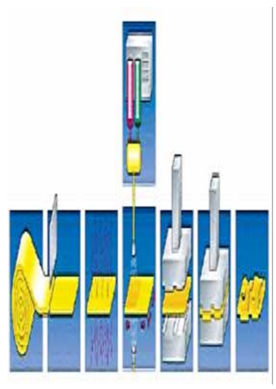
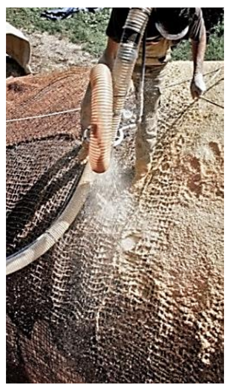
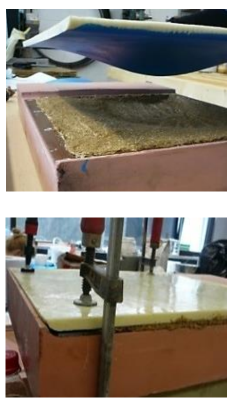
B 3.3.2. Agro-fibres thermoset biocomposites-processing possibilities

Most of the previous researchers focused on the continuous industrial natural fibres' types, that can be either manufactured into yarns or fleece to be easily wetted by the resin, mostly through spraying techniques. These methods consume less resin amounts.

In the case of straw and agricultural by-products' fibres, yarns' making is not a readily available option, due to the natural structure of the agro-fibre, that is short and splitting which doesn't allow to form yarns directly from it. In some researches, novel microfibrils with high quality that can be spinned and applied in textile industries were reachable through (Youyu, 2011). But inspite of this, these technologies haven't still proven themselves on an industrial-scale.

Commercially, the most applicable types of applying straw and agro-fibres within thermoset binders, depend mainly on short fibres, the same as in the case of thermoplastic binders' appliance. The short agro-fibres are either mixed with longer natural fibres, through needle technology to form mixed fleeces, as described in the last chapter, (Wimmer, et al., 2007), or through wetting the straw fibres in the resin bath, then spraying them or laying them in the desired mold, or heat-pressing them for dehydration and completing the chemical processing.

Through the following table, a summarized review is illustrated on the possible production methods of straw and short agro-fibres free-oriented thermoset biocomposites, whether for the building sector, furniture or possible automotive applications:

Processing stages	Production Option 1	Production Option 2	Production Option 3
1st Process: Preparing and refining the fibre	Mixing the straw fibres with other natural fibres using needle technology to form fleece textile	Cutting the fibres and sieving them to the desired lengths	
	 1	 2	
2nd Process: Semi-finished Product	Spraying the fleece with the resin using nozzles from 1 or 2 directions, then pressing with heat appliance OR Applying resin transfer technology within closed vacuum molding	Wetting the short fibres/ mixing with the resin then spraying the mixture applying closed vacuum molding	Wetting the short fibres/ mixing with the resin + applying press-closed molding with vacuum assistance
	 3	 4	 5

3rd Process: Final Product	Lamination/ Milling/Laser-Cutting/ CNC-drilling		
	 6	 7	 8

*Photos credits: 1: (Wimmer, et al., 2007); 2: H.Dahy; 3: FNR (Fachagentur Nachwachsende Rohstoffe e.V., (*www.biowerkstoffe.fnr.de*); 4,7: Organoid Technologies GmbH; 5: H.Dahy; ; 6: (Müssig, et al., 2007); 8-up: raumprobe; 8-down: B.Miklautsch*

Table B3-5. Illustration of the possible compounding, machining and final product manufacturing processes of agro-fibre thermoset biocomposites.

B 3.3.3. Agro-fibres thermoset biocomposites- Review

Value of natural fibres in automotives was realized through the achievement of lower weights and high vibration absorption levels, which was found to reach much satisfying rates than artificial fibres, (Krishnan, M.; Gruntechn Polymer Consultants, 2013). Thermoset resins' application to bind the natural fibres would then bind the advantages of both medias and achieve the needed weathering-resistance achieved by the matrix and the vibration-absorption achieved by the natural fibres, for external vehicles' bodies' manufacturing.

Similarly, façade and external architectural applications would need the same collaboration between the natural fibres and thermoset binders, to reach much higher weathering resistance, to increase the efficiency of agro-fibres through enabling them to serve in external applications as well and not only limited to interior ones. Wind-vibration and weathering effects on the façade panels made from the proposed agro-fibres thermoset composites are to be expected.

a. Banana fibre with fossil-based epoxy resin

Many researches took place, applying agro-fibres and thermoset matrices to reach high-added value products. From these researches was a project made by the team of Suzuki Motor Corporation to use the banana fibre, from the agro-byproducts' stream, and they applied it to epoxy resin, again in the automotives' industry, to form the electric vehicle external body, as shown in Fig. (B3-20). The banana fibre was prepared in the form of mats, pigmented in green-color, then immersed with transparent epoxy resin, to preserve and show the banana mat's color, offering a special design effect and adding to the environmentally-friendly conception to the electric car.

Figure B3-20.Concept of using banana mat fibre and epoxy resin by SUZUKI in the electric vehicle's body, (Krishnan, M.; Gruntechn Polymer Consultants, 2013)

b. Agro-fibres with fossil-based polyester resin

Researches with agro-fibres using polyester resins were recorded by Hassan and Nada in 2003, (Hassan, et al., 2003), when they studied a number of different agro-residues' fibres including rice straw, bagasse and cotton stalks after esterifying them through applying maleic anhydride as a compatibilizer before being applied to the polyester resin media at different fibre loads (15-30%wt) and screened lengths (1,5-5,5 mm). The best fibre/polyester collaboration was recorded with rice straw, achieving the best mechanical properties; while the best UV-resistance was recorded by the cotton stalks contribution, probably due to the natural inner bark of the cotton stalks, which consists of natural UV-absorbing groups, as indicated by the authors. It was recorded that the highest mechanical properties at higher fibre loads (till 30%wt.) were only achievable when the straw fibre lengths were as short as possible (around 3,5 mm).

c. Rice straw (RS) with fossil-based unsaturated polyester resin

In another study for RS- unsaturated polyester biocomposite much earlier made in 1983 by the research team in Bath University in the UK, (White, et al., 1983), the value of using rice straw as an eco-filler and its value in achieving much cheaper biocomposites, than applying the fibre for reinforcement was here emphasized. The researchers revealed that comparing the RS fibre filled polyester, applying the fibre in its raw form and without applying extra compatibilizers, still lead to an increase in the mechanical properties of the composite in comparison to the pure polyester matrix by 2,5 times. But still, as here declared, comparing the outcome to other applied fibres with the same matrix, RS-polyester showed only half the mechanical efficiency shown by timber and GF (glass fibre) when applied. However, as here declared by the researchers and as here applied in this research as well, the debate of minimizing or preventing the pre-treatment of the fibre is suggested, as the costs of pre-treatment of fibres to improve the mechanical attitude is mostly overweighing any improvement in the mechanical performance.

This debate that exists since the 1980s is still not completely solved when combining straw fibres with organic matrices. The reason of this high difficulty is due to the high silica/lignin's presence within the external tissues of the fibres, which needs successive purifying processes to win the needed cellulose fibres, when the material developer needs to apply the straw fibre mainly for reinforcement, and not just as a filler.

B 3.3.5. Agro-fibre thermoset biocomposites- Market availability

Within the building and architectural market, structural elements out of composites of natural fibres retrieved from the agricultural residues doesn't still commercially exist. However, non-structural architectural panels and furniture applications are the only examples present in the contemporary markets.

a. Almond shells and fossil-based resins

This agro-fibre thermoset composite is present in the markets under the name of Duralmond®, (Duralmond GmBH), which is manufactured in Spain, is mainly for architectural applications. It is composed of non-structural elements out of crushed/ flour-form almond shells bonded by conventional fossil-based resin mixed with vegetable-oil based ones and additives, forming one of the rare commercial products based on thermoset molded agro-fibres' biocomposites. The molded composite is subjected to heat and pressure after combining the fibres with the binder. Within the polymerization process of the crushed almond shells/resin mixture, micro-pores are created to allow the material to induce positive thermal and acoustic insulation properties.

Out of this material, a series of internal and external applications, as well as designs' possibilities and decorations are offered, through the molding manufacturing techniques, Fig. (B3-21).

Almond shells are crushed and turned to powder form, before being bonded with the applied resin

Interior partition Module made and supplied by Duralmond, (Duralmond GmbH)

Duralmond® Material applied as Facade elements in the EME Fusion Hotel in Seville-Spain in 2008, (Duralmond GmBH)

Figure B3-21. Illustration of the almond shells thermoset biocomposite materials and possible applications

b. Agro-fibres and fossil-based acrylic resin:

Another commercial example for thermoset biocomposites out of agro-fibres, under the name of Organoid® is produced through the Austrian company Organoid Technologies GmBH, (Organoid Technologies GmBH, 2013). The combination of the mixture of short agricultural waste-based fibres and the fossil-based acrylic-resin is firstly prepared, then using a fibre-spray technique combined by a vacuum molding process, the mixture is sprayed on the desired form, before being sanded and finished in its final figure. This newly grounded company, since 2011, has managed to create individual objects like furniture units as well as possible mass-production multi-purpose acoustic-decorative panels. The material is only suitable for interior dry applications, and could contain natural fibres uptill 80% by mass, (Egger, 2013). The fibres' mixture is applied using hybrids of different agro- fibres depending on the mechanical, technical and aesthetic goals needed to be reached.

Through the following figure, Fig. (B3-22), the sequences of producing furniture pieces using closed molding of agro-fibre-acrylic based composites are shown.

1- Mold Making process of the IOYO Pouf , Photos: Tischlerei R-UM, after (Scadeczky, 2012)

2-The mixture is distributed through hand work within the mold before being vacuumed and 'backed' , Photo: Organoid® Technologies, after (Scadeczky, 2012)

3-The final IOYO chair after the trimming and sanding processes, (Organoid Technologies GmBH, 2013). Photo:Nofrontiere

4-The furniture piece applied in interior spaces, (Organoid Technologies GmBH, 2013). Photo:Nofrontiere

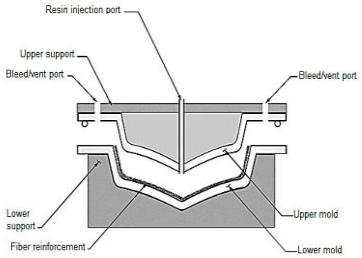
Figure B3-22. The manufacturing processes and application possibilities of a furniture model composed of a thermoset agro-fibres biocomposite, developed by Orngaoid Technologies GmBH-Austria

As illustrated, no green agro-fibre thermoset biocomposites are available in the contemporary markets. Green natural fibre thermoset biocomposites are rarely recorded in the state of the art through history. One of the early attempts was recorded in 1926, (Pal, 1984), when experiments were applied to form Jute- shellac composites. In the contemporary architectural applications, few green natural fibre thermoset biocomposites are applied whether for interior or exterior applications. Within the following, two examples of these applications are illustrated, that are suggested to be replaced through the developed green agro-fibre thermoset biocomposites that are developed within this research.

B 3.3.4. Green natural fibre thermoset biocomposites- existing architectural applications

a. Indoor architectural application: reLEAF chair, USA

In the University of Arts in the USA, a number of trials using different natural fibres took place including flax, jute and derived cellulose from the fibre-crops' resources, as well as recycled paper and chicken feathers from the commodity solid residues' resources, (Dweib, et al., 2005). The developers applied these natural and recycled agro-fibres with a soy-oil based low-viscous bioresin, applying a vacuum-assisted resin-transfer molding process, Fig. (B3-23), for manufacturing the semi-finished products that were developed for both structural and furniture purposes.



The Vacuum Assisted Resin Transfer Molding (VARTM) Process, (Molds Online, 2013)

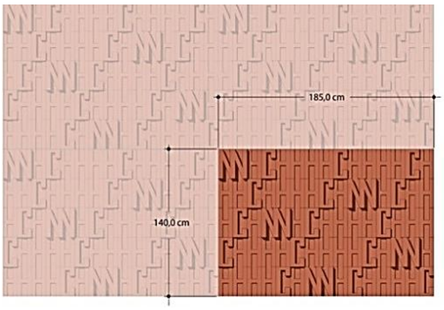
The manufacturing of the chair in process with room-temperature cured acrylated epoxidized soy oil (AESO), (Thompson, 2004)

The chair in its final form, (Thompson, 2004)

Figure B3-23. Illustration of the manufacturing process of the reLEAF chair from flax fibre mats and soy-oil resin

b. Exterior architectural application: Green Façade, the Netherlands

This is another attempt of developing natural fibre thermoset composite panels in architectural applications for exterior uses, in the form of façade panels, Fig. (B3-24). This green biocomposite is composed of hemp fibres in the form of fleece-mats bonded by a bio-resin derived from soya beans, linseed oil and wastes from biodiesel production, to form green biocomposite façade panels that were manufactured with the help of NPSP Compositen BV and Nabasco® Lab technology and was designed by the architect: Studio Marco Vermeulen in Netherlands. The façade panels were designed and fixed to form the external skeleton of a gas transfer station in Dinteloord, a village for future developments for green-based economy in the Netherlands. The façade panels' dimensions are 140 cm x 185 cm, with a series of letters printed on them, in relief. The letters are C, H and N, representing the chemical symbols of the main components of natural gas: Carbon, Hydrogen and Nitrogen, which was the main design concept, (© Studio Marco Vermeulen).



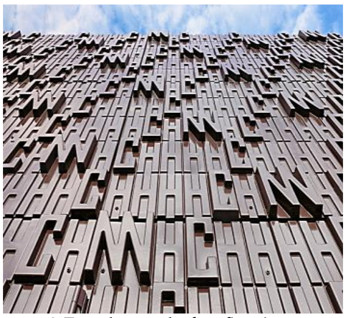
1-Facade panel design and dimensions according to the architect

2-Mold before applying the fibre, resin and vacuum

3-Re-charge after molding, presenting external façade skin

4-Inner hemp fleece for insulation purposes

5-Final panel after vacuum molding process



6-Façade panel after fixation

7-The developed panel was also applied as a door unit

8-The whole gas unit building in an isometric view

Figure B3-24. Illustration of the product design, manufacturing procedures of the green façade thermoset panels and the final outcome for the gas station building in the Netherlands. Photos' credits: © Ronald Tilleman and © Studio Marco Vermeulen

B 3.3.6. Advantages of green agro-fibre thermoset biocomposites:

Economic and ecologic values

a. Soybean oil, sunflower oil and corn oil have similar structures and have abundant amounts worldwide. Accordingly, the successful conversion of the soybean and others to a polymer similar to epoxides should result in an expanded bioresins and biocomposites market, replacing the expensive non-renewable fossil-based resins. Combining the abundant cheap agro-fibres with bioresins would double the value of the final green thermoset biocomposite achieved.

b. Recycling of thermoset biocomposites are either through energy-winning via thermal pyrolysis, or through smashing and applying it as an eco-filler in another biocomposite, based on the same components, to reach optimum performances, (von Buttlar, et al., 2004). In case of green thermoset biocomposites, recycling options is expected to be easier and much worthy, in case both components are biomass-based as here suggested and developed.

B 3.3.7. Conclusion- suggested development

Green agro-fibre thermoset biocomposites do not still exist in the contemporary architectural markets, inspite of their high potentials and advantages. Accordingly, the introduction of cereal straw as a cheap agro-filler is here applied to increase the economic and ecologic value of the green agro-fibre thermoset biocomposites targeting architectural applications. In this research and through a half-mechanized method, 40% -50% of fibre load by weight was reachable to produce prototypes of free-form façade panels of scale 1:1, that can reach to 80% wt. in case of the molding process' integration with the vacuum appliance, as previously described when agro-fibres' spray method was applied by Organoid GmbH. These panels' manufacturing process is illustrated in Chapter D.

In the third part of the following chapter, Rice Straw (RS) is applied in its raw chopped form at 20% fibre wt. with 2 bio-resins, where one of them needs thermal treatment to harden and the other hardens at room temperature. Both green rice straw thermoset biocomposites were compared at fibre load of RS- 20% wt. to a another third developed biocomposite composed of RS and a fossil-based epoxy resin at the same fibre load by wt. for referencing and comparison purposes. The biocomposites are then analysed according to their mechanical properties, fire-resistance, free-weathering performance and other technical properties.

C.

Rice Straw Biocomposites Developments

C. Rice Straw Biocomposites Developments

C 1. Rice Straw fibreboard with elastic binder

As described in the previous chapter, dry-based fibreboards manufacturing which is the ecologically preferred manufacturing method of fibreboards, is overwhelmed by non-recyclable thermoset binders. Agro-fibreboards with elastic binders still don't exist in the contemporary building market. These kinds of fibreboards offer different geometrical advantages that are highly demanded in architectural applications.

The aim in this context is to apply the maximum amount of straw fibres into a fibreboard of possible versatile and flexible forms, to suit flooring mats as well as free-form interior fittings and furniture. In this part, rice straw will be combined with an elastic binder to manufacture high density straw fibreboards with a high fibre ratio of 80% wt. without chemical modification. In the following chapter, the possible applications of this fibreboard in architecture are illustrated.

The development here was settled to be offer ecological end-of–life options, including recyclability and biodegradability, where the later was tested through a soil-burial test that simulated compost conditions, which was applied to proof the possibility of the biodegradation of the developed panels' components under aerobic bacteria's action within the applied testing conditions.

C 1.1. Main fibreboard components

Selected agro-fibre: Rice Straw (RS):

The rice straw was mainly purchased from Egypt, from "El Sharkeya" City in North-Egypt, after the cultivation seasons of the years 2010 and 2011. The samples were collected from the fields after being natural dried, before being baled. Other rice straw samples were purchased from Senegal, which is another African country. The bales were de-baled, purchased and sent to Stuttgart-Germany, through the researcher, and a number of cutting methods were tested, to select the optimum shredding/milling method of the fibre, before combining it with the selected binder.

Selected elastic binder and production technique

Selected elastic binder: Vinnex® LL 2505 (Vin.)- provided from Wacker Chemie AG

The selected binder is in the form of powder (ground scrap) of 370-520 Kg/m^3 density. The binder selected is from the thermoplastic elastomeric group of polymers (TEP), where the binder is a mixture of vinyl-acetate base (which is a rubbery synthetic polymer) and ethylene Copolymer base with a high ratio providing high elasticity, (EVA). The elastic binder selected has the market name: Vinnex® LL2505, abbreviated as (Vin.), which is free from plasticizers and Chlorine as indicated in the product's data sheet.

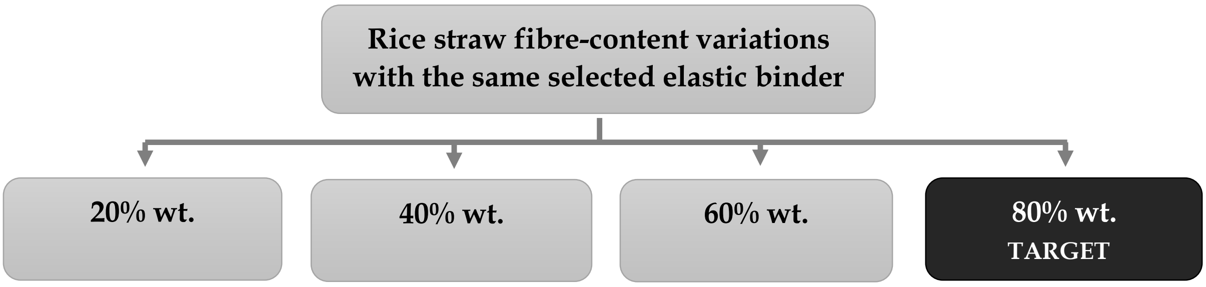
The production method is an eco-friendly dry production technique, where available plastic industrial production lines can be applied. In order to have the possibility to mix the RS fibres and the elastic binder at room temperature prior to the dosing process, a powder-form elastic thermoplastic binder was selected. This method would enable a high economical profit, since the RS and binder can be mixed homogenously on a dry basis, according to the desired recipe in one phase, skipping the complicated multi-stages of the dosing process that takes place in other natural fibre composites' manufactory, which is itself an important industrial aspect that can decrease the final product's cost.

C 1.2. Comparison methodology

The rice straw fibreboard was aimed to have the maximum possible fibre mass load to achieve the economic, ecologic and technical outcome of this development.

To monitor the technical and physical changes in the developed fibreboard as the fibre mass load increase, different specimens were prepared at different fibre loads by wt. at 20%wt., 40% wt., 60% wt., and 80%. The last mass load 80%wt. is the target mass load to be achieved.

Accordingly, comparison methodology is described as follows:



RS fibreboards' specimens with different fibre wt. loads are specified through the research using these symbols: [RS (20%) -Vin.], [RS (40%) -Vin.], [RS (60%) -Vin.] and [RS (80%) -Vin.]; where RS is the rice straw agro-fibre applied, Vin. is the elastic binder applied and 20-80% are the fibre wt. loads.

C 1.3. Rice Straw fibre preparation before compounding

C 1.3.1. RS fibre analysis

The RS fibres were chopped and burnt at 550°C to prepare the rice straw ash samples in the labs of the Institute of Food Chemistry (ILC) at the University of Hohenheim. The Egyptian RS ash weighed (15.1%) from the total dry straw sample's weight, while the Senegalian RS ash weighed (14.83%).

The inner chemical inorganic components of the two rice straw ash samples, were analyzed through the State Office for Agricultural Chemistry (LA-Chemie) at the University of Hohenheim, as follows:

mg/kg Ash	Al	Ca	Fe	K	Mg	Mn	Na	P	S	Si	Zn
Egyptian Rice Straw	3,566	16,630	3,599	80,573	11,657	1,561	33,071	2,326	4,666	313,113	129
Senegalian rice straw	2,065	18,801	1,553	80,218	6,893	2,937	1,917	6,451	4,628	343,817	70

Table C 1-1.The inner chemical composition of the inorganic ash components of rice straw samples.

It is clear through the previous illustrated table how high the silicon component is, in comparison to other in-organic ash components for both rice straw samples applied. In case of the Egyptian rice straw, silicon contents were around (66,5%) of the total dry weight of the rice straw ash meaning around (9,9%) of the whole rice straw weight; while it was around (73,3%) in the case of the Senegalian rice straw ash – meaning around (11,1%) of the whole rice straw weight.

Accordingly, the applied rice straw had pure silicon contents ranging from (9, 9% - 11, 1%) of the total straw weight. This high silicon content's reflection on the flammability attitude of the developed rice straw biocomposites, will be analyzed later throughout this chapter.

C 1.3.2. Inner humidity assessment

The inner humidity of the rice straw samples was measured in the Faculty of Chemistry-Institute of Inorganic Chemistry (AOC) - University of Stuttgart, according to American Society of Agricultural and Biological Engineers Standards (ASAE S358.2, 2006).

The chopped rice straw samples were weighed before and after their dehydration for 24 hours within a vacuum oven at 105 °C, Figs. (C 1-1, C 1-2). The inner humidity of the samples ranged between (6%- 7%), which indicates that the fibre was in an acceptable state to be mixed with the binder without further drying procedures, according to (Churchill, et al., 2005). Churchill stated in his patent that the moisture content of the natural fibre before being mixed with the polymer should range between (3%- 8%). Accordingly, the straw fibres were directly applied with their natural dry state with inner moist of (6%- 7%), without further dehydration, throughout the biocomposites' development stages in this research.

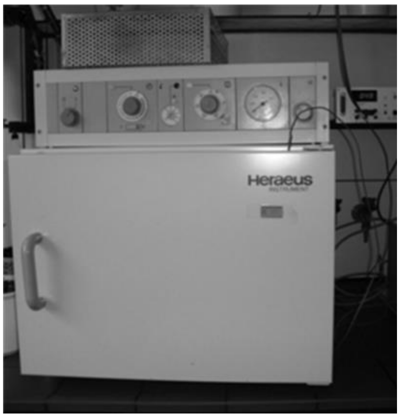


Figure C 1-1.Vacuum oven for samples' drying - AOC- University of Stuttgart

Figure C 1-2. Chopped rice straw samples dehydrated at 105°C for 24 hours

C1.3.3. RS chopping and grinding

The machines applied for shredding were as follows:

a- Regular fibre chopping machines were first trialed to chop the RS fibre to be applied later in the compounding processes, Fig. (C 1-3). The chopping process was not successful, regarding the huge dust fumes released, Fig. (C 1-4), not the chopping quality. These dust fumes could cause lung cancer when inhalated with large amounts. This would not be practical in industrial scale applications. Accordingly, other chopping machines were trialed for this purpose, to gain more environmentally and health-friendly fibre preparation methods.

Figure C 1-3. Regular fibre chopping machines without dust absorbers

Figure C 1-4. Huge un-healthy fumes released during the chopping process

b- A chopping machine provided from FRITSCH GmbH supported from the Institute for Agricultural Technology of the University of Hohenheim, functioned properly releasing no dust particles, due to the integrated system of the shredder (A) and the absorbing apparatus (B), linked to the collector (C), Fig. (C 1-5). This machine was applied for all RSF chopping procedures throughout all biocomposites' development procedures in this research.

Figure C 1-5.Chopping machine provided from FRITSCH GmbH, where the 3 components are combined: shredder (A), Hoover- vacuum absorber (B) and collector (C) .

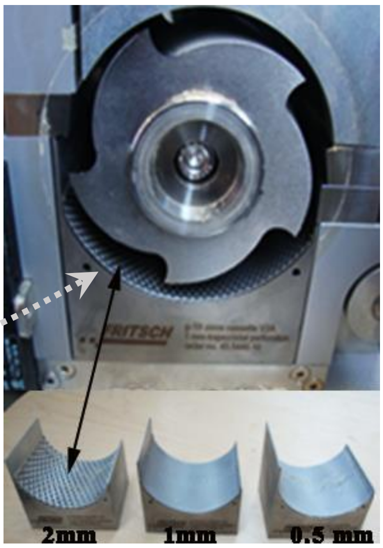


Figure C 1-6.The chopping head is integrated with the sieving systems

RS was chopped and applied without sieving, of fibre lengths ranging from 0,5-5 mm in addition to the released fines. The fines were not sieved on purpose since it has the highest silica fraction within the whole straw, as described by (Thompson, et al., 2002), Fig. (C 1-7). RS was applied in its natural dry state with an inner humidity not exceeding 7 %, which is an acceptable value before being applied to the binder within compounding, as indicated by (Churchill, et al., 2005).

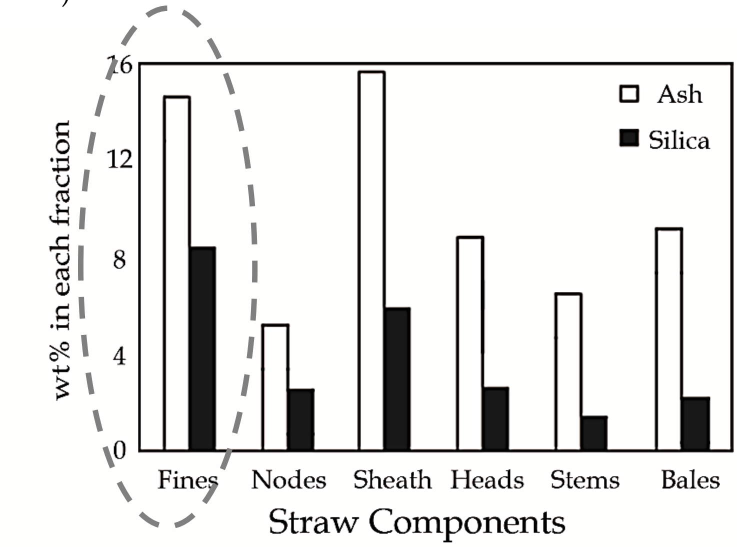
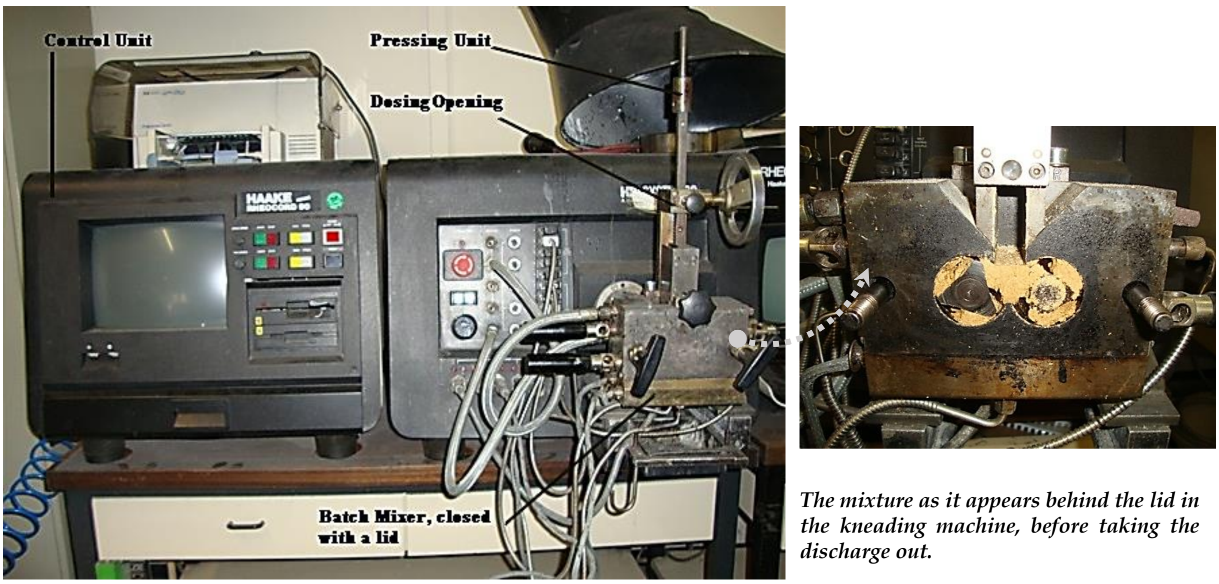


Figure C 1-7. Illustration of the ash and silica distribution in hand-separated straw fractions, (Thompson, et al., 2002 S. 4)

C 1.4. Compounding process and specimens preparation

C 1.4.1. Compounding process

Fibre dosing percentages were 0%, 20%, 40%, 60% and 80% by weight. The mixtures were mixed in room temperature prior to the feeding process, then fed gradually to the batch mixer machine, 'HAAKE Rheocord 90', Fig. (C 1-8), provided from the institute of polymer technology at the University of Stuttgart, at 50 rpm (rotation per minute) and 180°C.



The mixture as it appears behind the lid in the kneading machine, before taking the discharge out.

Figure C 1-8.The laboratory batch mixer (Kneader) machine applied for the compounding process

C 1.4.2. Specimens' preparation

a- The discharge was taken from the mixer and applied on a plate with Teflon® foil and a high temperature releasing agent, then pressed with a laboratory bench-top press-machine (Type P 200 E) from Dr. Collin GmbH- Ebersberg, Germany, Fig. (C 1-9), at 180°C- 200 Bar for 3-5 minutes.

b- The resulted plates were of 2mm thickness, that were cut using a small saw machine, Figs. (C 1-10, C 1-11), to produce the test specimens of 70x10x2mm, Fig. (C 1-12).

Figure C 1-9. Press machine used in thermal pressing of the discharge taken out of the batch mixer, to form the plate needed.

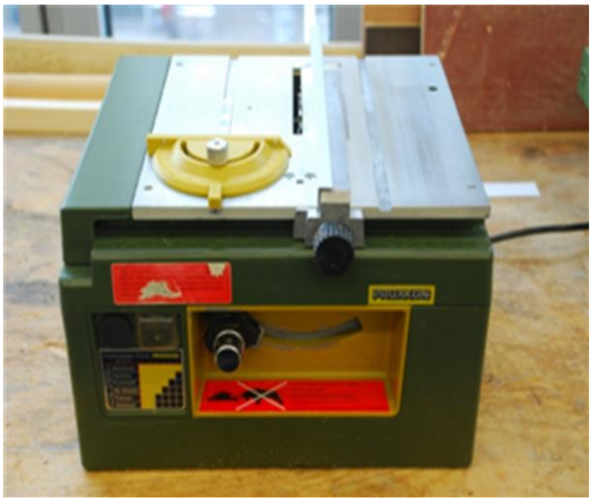


Figure C 1-10. The saw cutting machine applied in samples' preparation

Figure C 1-11. Cutting process of the boards produced according to the sample dimensions defined

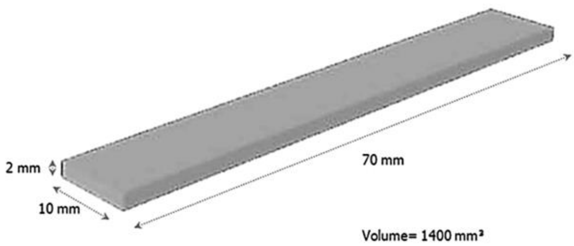


Figure C 1-12. Sketch illustrating the dimensions of the samples applied in the material's testing

C 1.5. Developed RS fibreboards- Properties analysis

The samples were studied both visually and analytically, through a number of tests, illustrating the technical properties of the developed materials at the different specified fibre mass loads. A number of properties were investigated that have important relevance in difference possible application possibilities in architecture, including dimensional stability, fire retardance, UV-resistance through free weathering and others. The tests and their results are illustrated as follows:

C 1.5.1. Density

The density of the RSF in its chopped form is equal to 40-100 Kg/m^3, (Jenkins, 1993), while the elastomer applied has a density of 360-460 Kg/m^3 in its powder supplied pure form, according to the Vinnex® product data sheet, before being manufactured.

The density of [RS (80%) -Vin.] was measured according to DIN 53 479 or DIN EN ISO 1183-1, (DIN e.V.: Deutsches Institut für Normung e.V., 2013), standard of density measurement in the labs of Institute of Polymer Technology (IKT)-University of Stuttgart at 23 +/- 1 °C. The other densities of [RS (20%), (40%), (60%) -Vin.] were measured in the labs of Fraunhofer Institute for Chemical Technology- ICT/Karlsruhe, using He-Gaspyknometer at 20°C. The produced RS fibreboards had the following densities:

Product's Name	Density [Kg/m^3]
[RS (20%) -Vin.]	1096
[RS (40%) -Vin.]	1156
[RS (60%) -Vin.]	1329
[RS (80%) -Vin.]	1099,9

Table C 1-2. RS fibreboards' densities at different fibre wt. loads

As displayed, all RS fibreboards are of high density regardless of the RSF content, which indicates that the elastomer's high density, after being cooked, defines the densities of the manufactured products. According to, (SImetric.co.uk, 2011), rubber in the powder ground scrap form, caoutchouc and manufactured/cooked form are of 481, 945 and 1522 Kg/m^3 densities respectively.

C 1.5.2. Water Absorption

Water absorption was measured after DIN EN 317, (Deutsches Institut für Normung e.V., 1993), to indicate the water absorption coefficient depending on the changes in the sample's thickness, which is the thickness swelling (TS), in %. The samples dimensions were quadrant as specified in the standard, but with smaller dimensions of 10x10x2 mm and were set in humid conditions of 65±5 % and temperature of 20±2 °C. The test samples, on which the experiments are performed, are not sealed on the sides to provide the most aggressive in-use water absorption conditions.

The results were then compared to DIN EN 622-5, (Deutsches Institut für Normung e.V., 2010), which regulates the technical requirements of the dry manufactured fibreboards. According to this standard, fibreboards' thickness lying between 1.8-2.5 mm have accepted thickness swelling until 45% for boards that will be applied in dry conditions, as in this case.

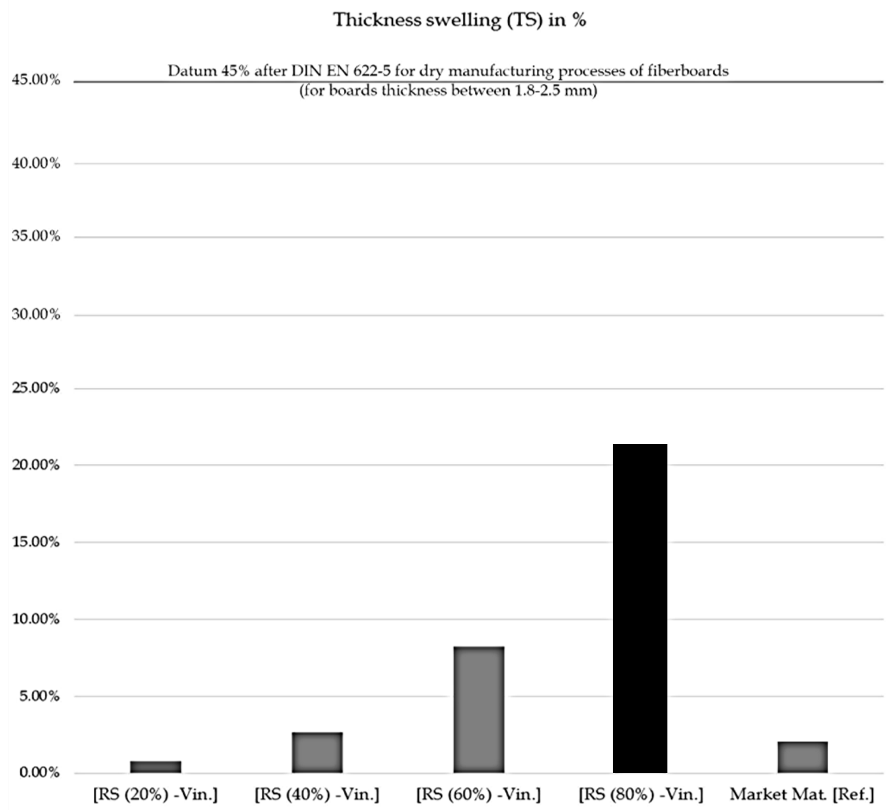
Inspite that the tested samples were smaller than that specified in the standard, it is clear through the graph, Fig. (C 1-13), the big gap between the allowed thickness swelling after DIN EN 622-5 and the thickness swelling measured from the developed samples, which indicates that the samples should still fall in the accepted range of thickness swelling. Accordingly, the samples' TS results were compared to the 45% TS as a datum. In addition, a market material composed of polyurethane elastic binder combining small percentages of mixed wood fibres and cork particles was applied for comparison.

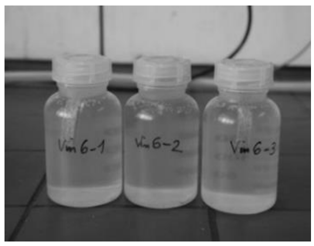
The results indicated that the water absorption increases whenever the fibre percentage increases till it reached the maximum TS at RS-80% wt., recording 21%.

Comparing these results with (Halvarsson, 2010) , who developed straw boards with UF and MDI resins, as illustrated in the last chapter, and inspite of the chemical additives, defibrillation and thermal treatment, water absorption after 24 hours immersion was recorded to be lying between 15-30%. The market material recorded 2% of TS, which was very similar to the fibreboard at 40%wt.-RS that recorded ca. 3% TS.

Since these developed elastic straw boards were merely composed of raw straw without applying any extra additives, then these 21% of water gain of the highest fibre load- 80% RS- can be much decreased and improved when compatible agents would be applied to increase the bonding between the fibre and the matrix. The coupling agent which would be recommended in this case is silane coupling agent.

In another study by (Moa, et al., 2003), water absorption tests of MDF straw particleboards, that were developed using raw and bleached straw, were applied. Within these fibreboards, different binders were applied including MDI (Methylene Diphenyl Diisocyanate), UF (Urea Formaldehyde), SF (Soybean Flour) and SPI (Soybean Protein Isolate). The developed boards' water absorption recorded 47,5% with raw straw and 34,2% with bleached straw after 24 h of water immerse.





The samples are immersed in distilled water, for 24 hours.

Figure C 1-13. Thickness swelling percentages of the straw fibreboards at different straw filling ratios after 24 hours, in %

C 1.5.3. Mechanical Properties

a. Tensile strength properties

The uni-axial tension tests were applied using a Zwick/Roell machine, Fig. (3-21), provided from the test lab of the host institute- itke- University of Stuttgart. The testing conditions were specified as follows:

Pre-load: 0,01 N/mm², Pre-load speed: 10 mm/min, Test speed: 50 mm/min. Since the sample is only 70 mm length, the distance between the fixed nodes indicated was fixed to be 25 mm, Fig. (C 1-14).

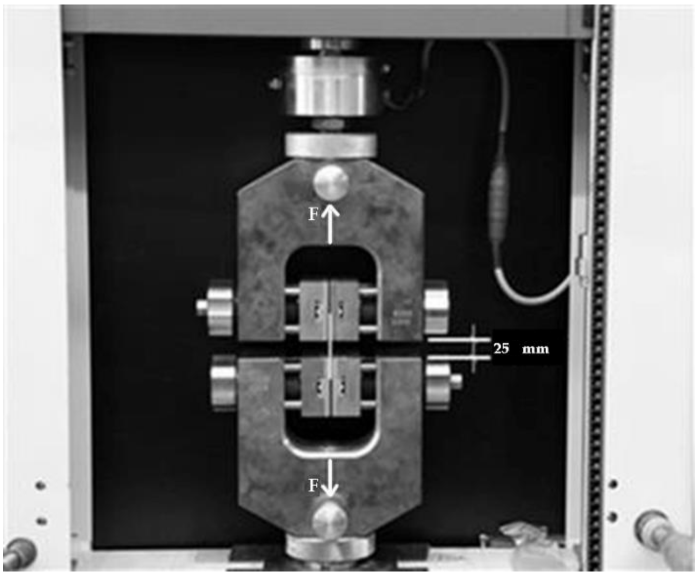


Figure C 1-14.Illustration of the fixation conditions and distance of the sample within the machine

The material's elastic properties are decreased and E-Modulus increased as the fibre percentage increased, Fig. (C 1-15), reaching 28,91 N/mm² at 80% fibre load in comparison to 0,42 N/mm² at 20% fibre load, increasing around 69 times due to the increase in the fibre load. The tensile strength increased almost continuously with the fibre load increase, except at 60% load, as a drop happened, then increased again at 80% fibre-load as indicated in Fig. (C 1-16). The samples' tensile strength was 1,38 N/mm² at 20% fibre load, reaching 2,60 N/mm² at 80% fibre load by weight, which is enough to handle the material through transportation, mechanical and manual handlings and installations, without being damaged or negatively affected.

The high density of the developed RS-fibreboards indicates the high resistance possibility towards impact forces and crashes, which could make the materials applicable for cushioning applications. However, extra mechanical testing should be applied to check shock and vibration resistance.

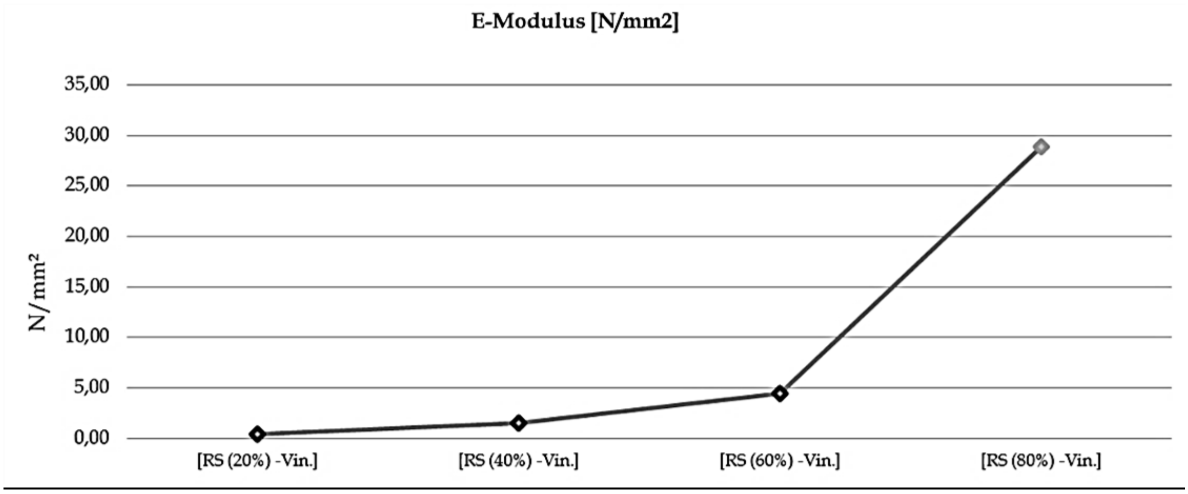


Figure C 1-15. The tensile stiffness increased 69 times at 80% fibre load than that elastic biocomposite of only 20% fibre load.

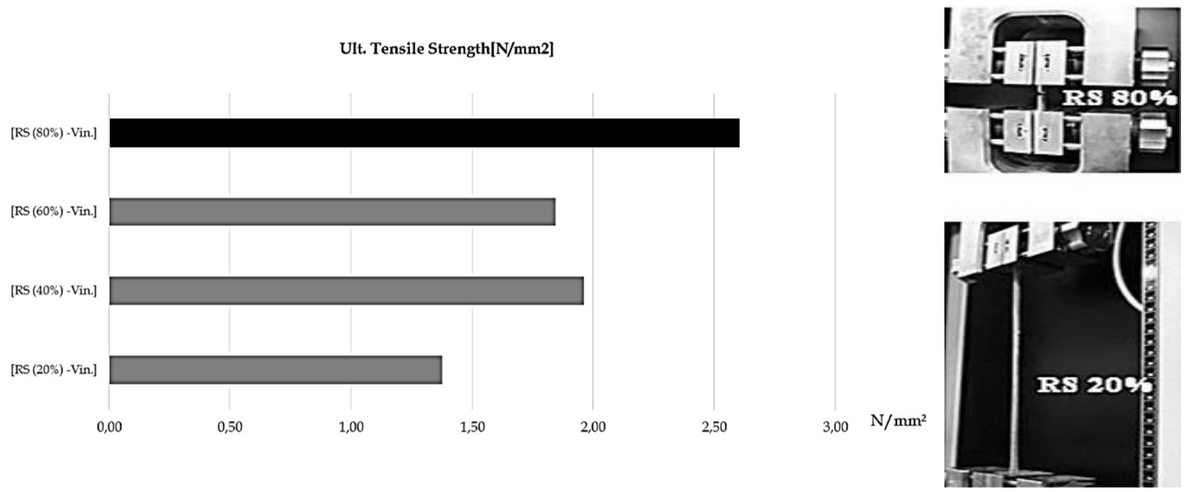


Figure C 1-16. The elasticity decreased and the stiffness increased as the rice straw content increases.

The developed materials were also tested under static loads to measure thickness losses, which reflect an important material characteristic, which is hardness represented in its residual indentation and indentation resistance, when the materials would be applied in flooring applications, especially for sports spaces and similar usages.

b. Residual indentation properties

The tests were applied to define the residual indentation after static loading, after DIN EN 433: Resilient floor coverings, (DIN Deutsches Institut für Normung e.V., 1994) that simulates the furniture loads; and the resistance to indentation of elastic surfaces for sport areas after DIN EN 1516, (DIN Deutsches Institut für Normung e.V., 2000). Each material was tested using 3 samples for each test type, and then the average was calculated.

Within the residual indentation DIN EN 433, the sample was pressed with a cylindrical test stamp of 1 cm² area with a force of around 50 Kg, for 150 minutes, then the load was removed and the sample was left to recover for another 150 minutes, then the permanent loss of thickness was determined. This simulates the pressure of heavy furniture's appliance on the floor.

Sample's Name	Thickness loss direct after load removal	Thickness loss after 150 minutes from load removal
[RS (20%) -Vin.]	1,25 mm	0,67 mm
[RS (40%) -Vin.]	0,86 mm	0,55 mm
[RS (60%) -Vin.]	0,92 mm	0,74 mm
[RS (80%) -Vin.]	0,27 mm	0,14 mm

Table C 1-3. Residual indentation of the developed materials according to different fibre loads, after DIN EN 433

Linoleum, as a reference material, has a residual indentation lying between 0,07-0,4 mm, after DIN EN 433, (BauNetz®). Comparing the developed materials to linoleum, comparable indentation performance can be deduced, especially with [RS (80%) -Vin.] and [RS (40%) -Vin.].

c. Indentation resistance properties

As for the resistance to indentation, after DIN EN 1516, the sample was exposed to a cylindrical test stamp of 25 mm diameter and a force of 500 N (equivalent to 50,99 Kg) for 5 hours. The deformation was measured after 5 min. from load lifting, then after 24 hours at a residual load of 3N (around 0,31 Kg) in both time intervals after the higher load's uplifting. The mean value of the residual indentation measured in these conditions after 24 hours after the end of exposure was assessed in accordance to this standard to be maximum of 0,5 mm difference.

Sample's Name	Thickness loss direct after load removal and 3 N appliance for 5 minutes	Thickness loss after 24 hours from load removal and 3N residual load appliance
[RS (20%) -Vin.]	1,11 mm	0,24 mm
[RS (40%) -Vin.]	0,61 mm	0,31 mm
[RS (60%) -Vin.]	0,61 mm	0,43 mm
[RS (80%) -Vin.]	0,11 mm	0,02 mm

Table C 1-4. Resistance to indentation of the developed materials according to different fibre loads, after DIN EN 1516, (DIN Deutsches Institut für Normung e.V., 2000).

As declared, in all fibre load percentages from 20-80%wt., the permanent change in the thickness did not exceed the defined limit according to the standard DIN EN 1516, which is 0,5 mm. This shows that the developed material has a high resistance to indentation after the high loads that could be available within sport halls, which indicates the possibility of applying the developed materials in sport activity areas and in cushioning services.

C 1.5.4. Thermal and acoustical insulation performance

The thermal attitude of the [RS (80%) -Vin.] was examined in IKT-University of Stuttgart, for a 10 x 10 x 2 mm sample, at normal room temperature (average of: 24 °C) , using LFA 447 apparatus, after being dried at 40°C for 96 hours, resulting in a mass loss of 3,6%. The examination's result indicated that the material cannot be applied as a thermal insulator. The thermal conductivity was found to be 0.187 W/m.k, meaning R-value (thermal resistivity) of only 0.011, which is normally taken as an indicator to determine the insulation materials properties. This R-value is very low to be applied as a thermal insulator, due to the high density of the material (1099.9 Kg/m^3). In addition, the specific heat (C) was also measured within a temperature range between (-40 °C and +40°C). The specific heat increased rapidly from 1,27 J/g.°C at 20°C to 1,38 J/g.°C at 40°C, within 2 minutes. This also indicates the same outcome, that the material does not suit to serve within thermal insulation applications.

Materials of accepted thermal insulations range from low to medium density-materials, according to (TIASA, 2001); where low density materials have a high proportion of small voids that inhibit convective heat transfer because of their small size. Whenever the voids decrease, the density increase and the convection (heat transfer) is increased through the solid mass of the material. Accordingly, higher density materials have poor thermal insulation behavior. On the other hand, higher densities affect positively the sound insulation behavior of the materials, meaning the acoustic behavior. As indicated by (Koizumi, et al., 2002), the acoustic behavior is better whenever the density increases. This relates to the number of fibres per unit area that are increased at higher board densities, hence energy loss increases as the surface friction increases and the sound absorption coefficient increases. Denser structures perform better for frequencies above than 2000 Hz, (Seddeq, 2009). However with higher stiffness, the sound transmittance increases, which means that the sound transmittance resistance decreases as the stiffness increases, according to Beiblatt 1 zu DIN 4109, (DIN Deutsches Institut für Normung e.V., 1989). Accordingly, [RS (20%) -Vin.] and [RS (40%) -Vin.] are expected to have better acoustical insulation performance being more elastic and of high density, while [RS (60%) -Vin.] and [RS (80%) -Vin.] are expected to have poor acoustic insulation performance.

In addition, it is generally known that rubber and elastomers are of expected acoustic insulation properties, with a long history within this field, as indicated in many researches including (Capps, 1989), (Roland, 2003). Many rubber based products are spread in markets, as Regupol® and explored in patents, for sound insulation specifically, as in (Kim, et al., 2013).

It was not possible to measure the acoustic performance of the developed materials, due to financial limitations, but according to the previous analysis, it can be concluded that the developed materials with less fibre load (as in the case of 20% and 40% fibre load), are accordingly expected to provide low acoustical transmittance, hence can be applied for acoustical flooring applications. However, before practical appliance of the material, sound absorption should be tested.

C 1.5.5. Morphological Examination

The samples were examined under a classic light microscope, Olympus SZX9 in the Institute of Inorganic Chemistry (AOC) - University of Stuttgart.

The examination was applied on the fracture surface of the samples, released from the tensile test, as well as on the surface. The images are illustrated as follows:

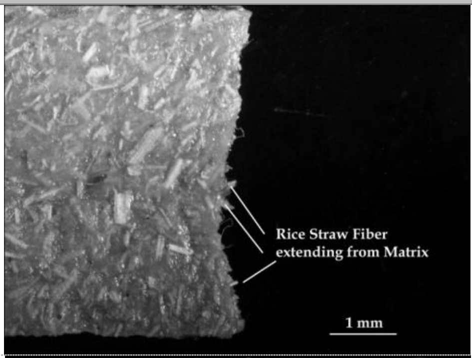
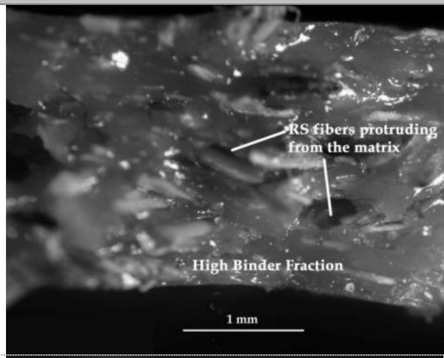
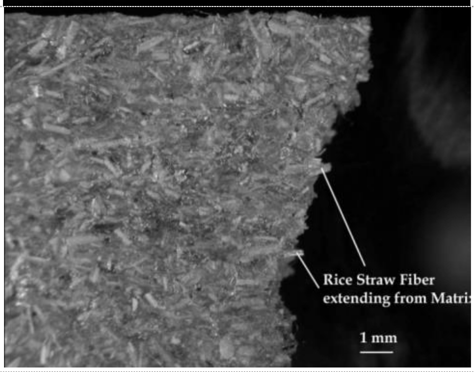
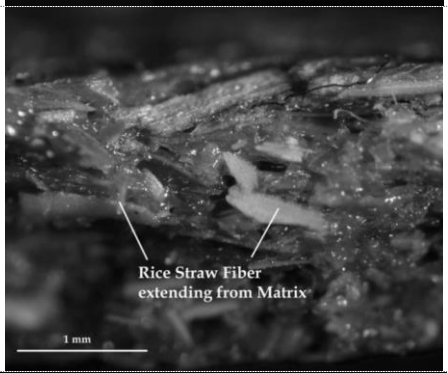
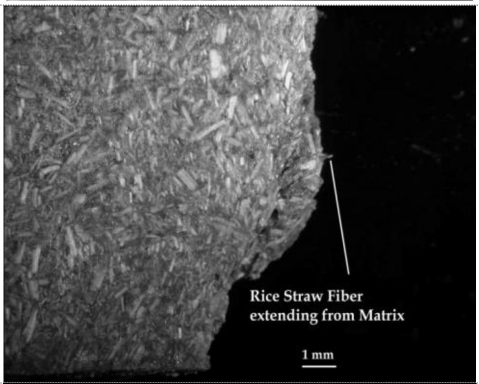
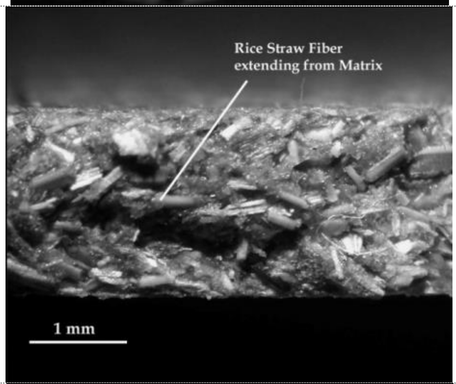
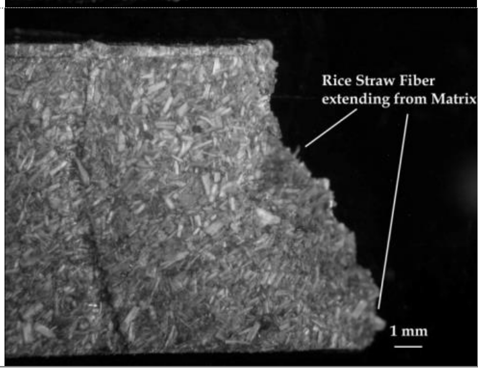
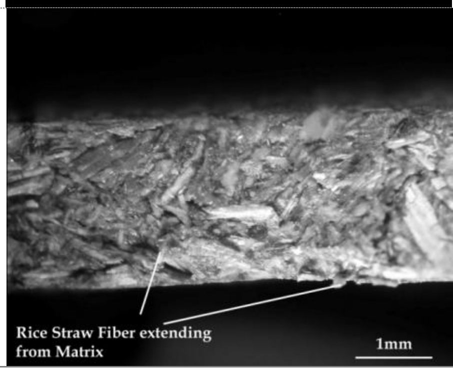
Sample Name	Surface	Section
[RS (20%) -Vin.]		
[RS (40%) -Vin.]		
[RS (60%) -Vin.]		
[RS (80%) -Vin.]		

Table C 1-5.Microscopic analysis of the fracture and the surface of the elastic rice straw fibreboards' specimens after the tensile strength test, with different fibre loadings of 20%, 40%, 60% and 80% respectively.

Through the previous morphological analysis, it can be deduced that the fibre/matrix interface was good, as the fibres were observed protruding through the fracture section, which resulted from the tensile strength test. Even though, it is highly recommended for future further investigation on this same composite material to use appropriate compatible agents that can improve the bonding interface between the fibre and the matrix, hence improving almost all material's properties, including water absorption resistance. According to (Genieva, et al., 2011), it was concluded that silane-coupling agent is the recommended compatible agent for silica enriched straw/husk and rubber. Accordingly silane-coupling agent is recommended as a compatible agent for further investigations of the developed RS fibreboards.

C 1.5.6. Free weathering

a. Test Description and Conditions

The samples were fixed on the top of the 10- multi story building of the Faculty of Architecture-University of Stuttgart in Stuttgart City in Germany. The specimens were fixed on a test rack at 45° directed towards, without opposing obstacles that would negatively affect the test according to DIN EN ISO 877, (DIN e.V.: Deutsches Institut für Normung e.V., 2011) , and applied for 24 months – Fig. (C 1-16). Each three months, photos were taken for the specimens and visual observations were accordingly concluded, Fig. (C 1-17).

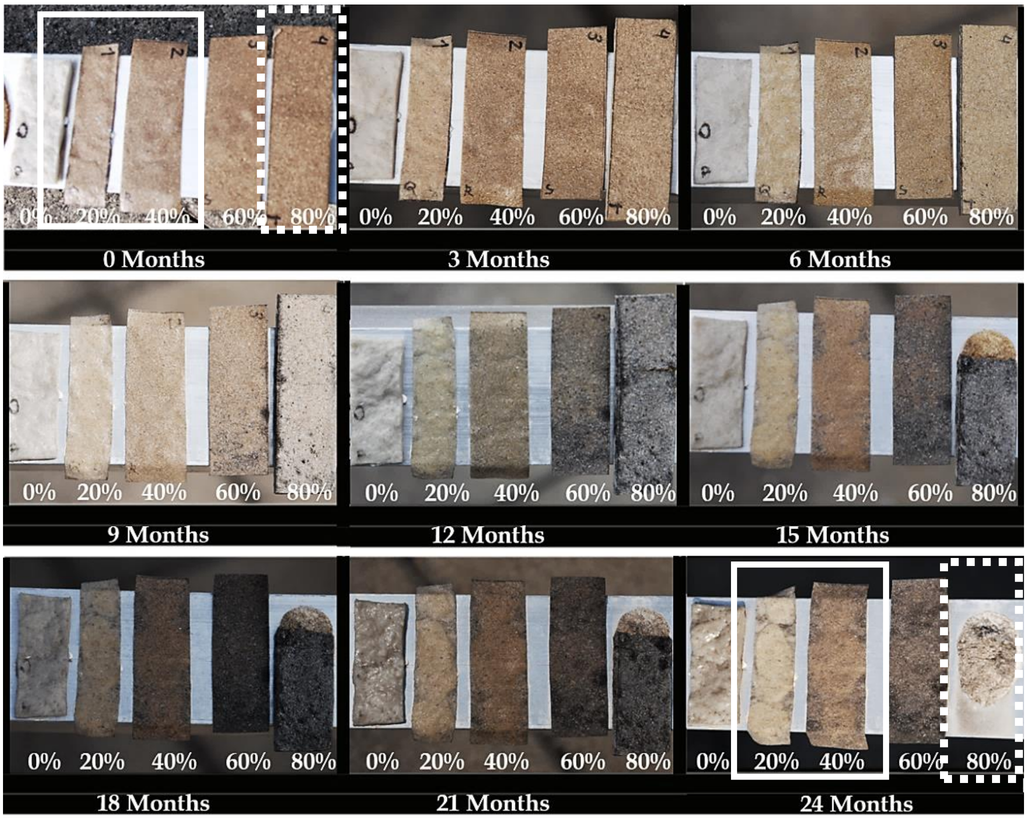
Figure C 1-16. Photo of the test rack fixed on top of the Faculty of Architecture building in the center of Stuttgart- Germany

After the end of this testing time interval, no extra mechanical tests were applied on the specimens to measure if there's a loss in the mechanical properties or not, which is a vital test as well to show the mechanical behavior of the materials at these severe weathering conditions when applied exteriorly. Accordingly, this test only gives an indication of the weathering-resistance of the developed materials, but not a definite indication of their application feasibility in external applications.

b. Test results and evaluation

This exposure test was applied to provide an indication of the relative outdoor performance of the samples and not as a pure performance indicator method for outdoors. The results indicated that the examined boards, especially at higher straw loads percentages, do not suit direct weathering exposure (at 60% and 80% fibre wt.). Therefore, it is mandatory in case of external applications that the materials, especially of high fibre percentages, to be covered by a protecting sheet against direct sunlight and successive rainfalls. Otherwise, the materials should suit only indoor applications.

As previously illustrated, the white-framed samples indicate the limited defect in the samples with lower fibre-content, while those of higher straw-contents suffered from direct biological attack, that caused the final sample (of 80%-fibre load) to completely vanish-out after 2 years of weathering exposure, as its surface washed up gradually with time, as seen in the photos.



Note: apparent colors are original and un-modified colors. Any extra darkness or lightness appearing was due to differences in natural lighting within different weather seasons and climate differences.

Logo: *RS fibre boards with higher weathering resistance and lower fibre wt. load* *RS fibreboards with the lowest weathering resistance and the highest fibre wt. load*

Figure C 1-17. Figure showing the visual comparison of the RS elastic boards' specimens with different loading ratios after being subjected to natural weathering within 24 months.

C 1.5.7. Flammability Behavior

a. Test Description and Conditions

The samples were tested for their flammability behavior according to the UL 1694 "test conditions for flammability of small polymeric component materials", 2006, ((UL), Underwriters Laboratories Inc., 2006), due to the probes' size. The conditions that were selected to be applied here are considered severe in comparison to the classic UL 94, "Tests for Flammability of Plastic Materials for Parts in Devices and Applications", ((UL), Underwriters Laboratories Inc., 2006). Generally, it should be illustrated that test results cannot be taken as an exact evaluation of the material fire class that can be directly applied in building construction or as a finishing or cladding material, but rather considered as a general evaluation of the flammability behavior of the examined materials.

To investigate the materials flammability for building construction behavior, other testing standards should be applied (like DIN 4102-1/small burner test or SBI test/ Single Burning Item Test to be classified according to the new European standard DIN EN 13501) for the complete building component. The burning time applied on the specimens were 20 seconds, according to the volume of the specimens applied, which were limited to 1400 mm^3, while the whole specified standard is applicable for small samples up to 2500 mm^3 volume.

The test took place in normal room temperature (approx.23°C) and without further material drying. The burning position was settled as indicated in Fig. (C 1-18).

The apparatuses applied are described as follows:

a. Laboratory fume hood with (Inside volume: 1 x 0,75 x 1,5=1,125 m^3), Fig. (C 1-19), to provide enough oxygen for normal combustion to obtain accurate results. The chamber was provided by movable safe glass screen for observation and test control.
b. Laboratory small burner of approx. 60 mm length, 0,5±0,1mm inner diameter and approx. 0,8mm outside diameter. The burner was connected with a gas supply and had a flame height of max. 12±1mm. If the burner is titled to avoid droplets falling on it, the flame height is of approx. 8 mm.
c. Laboratory ring stands to enable positioning in the required angle and height.
d. Digital time device with 0,5 sec accuracy and measuring scale in mm.
e. Cotton pieces (indicator) cut into 50 x 50mm, placed under the hanged specimen.

After the flame application for the specified time interval (20 sec.), the burner was withdrawn for approx. 150 mm away and the timing after flame application till the flame ceased was recorded (t_{b1}). After the second flame application, the time was again recorded from the second flame application till the second flame ceased as well and stopped flaming or glowing, which is the after flame time that was recorded as well in seconds (t_{b2}).

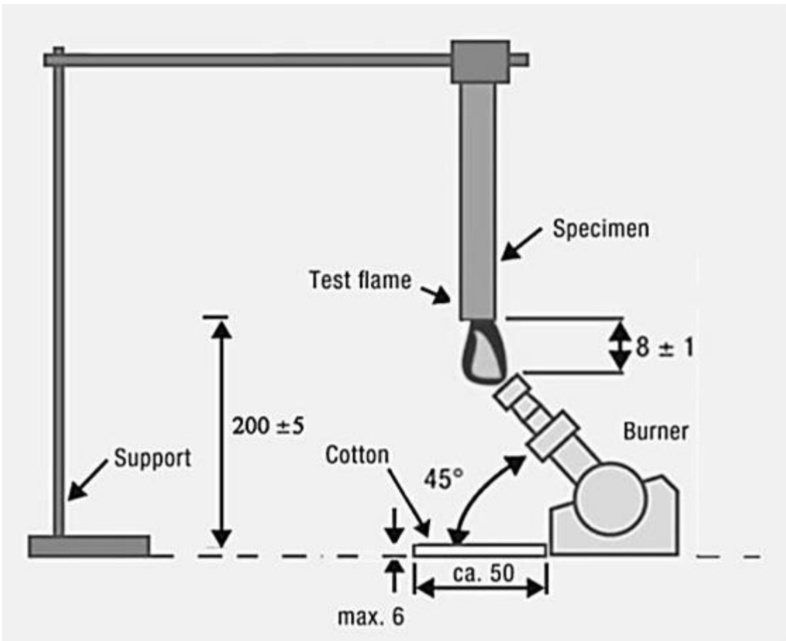


Figure C 1-18. Illustrating diagram showing the burner's positioning in respect to the sample (vertical position) and indicator according to the applied UL 1694 testing standard, ((UL), Underwriters Laboratories Inc., 2006). Dimensions are in mm

Figure C 1-19. (a), (b): Illustration of the fume hood and the combustion chamber applied in the fire test.

b. Test results and evaluation

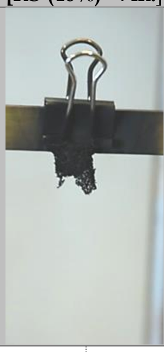
Specimen	[RS (0%) -Vin.]		[RS (20%) -Vin.]		[RS (40%) -Vin.]		[RS (60%) -Vin.]		[RS (80%) -Vin.]	
Photo										
[sec.]	$t_{b\,1}$	$t_{b\,2}$	$t_{b\,1}$	$t_{b\,2}$	$t_{b\,1}$	$t_{b\,2}$	$t_{b\,1}$	$t_{b\,2}$	$t_{b\,1}$	$t_{b\,2}$
Spec.1	134	-	100	-	75	-	62	-	12	48
Spec.2	157	-	90	-	70	-	55	-	58	-
Spec.3	145	-	98	-	75	-	55	-	58	-
Spec.4	128	-	102	-	72	-	60	-	61	-
Spec.5	117	-	94	-	62	68	55	-	46	-
Cotton Indicator Ignition (Yes/No)	Yes		Yes		Yes		No		No	
Complete consumption of specimen (Yes/No)	Yes		Yes		Yes		Yes		Yes, except first specimen (No)	
Notes	Completely burnt		Completely burnt		Traces of RSF appear at the clamp's end		The whole sample's form was preserved through the fibre		Best fire behavior achieved within this group	

Table C 1-6. Illustration of the fire test results of the RS elastic boards' samples at different fibre loadings (from 0%-80%) after UL 1694, and how this affected the fire behavior.

It was concluded that the fire behavior improves and the burning time decreases whenever the RS fibre filling ratio increases. Due to the severe burning conditions of the standard applied, it was not possible to deduce a specific material class of the materials tested, according to UL1694. However, [RS (80%) -Vin.] and [RS (60%) -Vin.] performed an appropriate flammability resistance, without adding extra flame-retardant additives, having no burning droplets on the cotton indicator and self-extinguishing in less than half the burning time of the developed material with only 20% fibre load, as previously shown. Accordingly, it is expected if the trials were repeated in other samples' dimensions under the conditions of UL 94-vertical test, with the appliance of the flame of only 10 sec. as flame application time, instead of 20 sec., and after the application of minimal mineral-based flame retardants' amounts, a UL 94-V0- difficult to ignite material class is expected to be reachable for [RS (80%) -Vin.] and UL 94-V1 - normal inflammable for [RS (60%) -Vin.], which are comparable to Building material class DIN 4102-B1 and B2 respectively.

C 1.5.8. Environmental assessment with respect to recyclability and biodegradability:

The material can be recycled, depending on its components: the natural fibre and the thermoplastic elastomer matrix applied. On the other hand, the material was also tested, if it has tendency to compost aerobically after its useful life time, as another end-of-life option, which became recently of great interest in different industrial scopes.

a. Definitions:

Biodegradation

It's a naturally occurring process when aerobic bacteria (in presence of light and oxygen) or anaerobic bacteria attacks the organic matter and breaks it down, releasing CO_2 (carbon dioxide) in compost aerobic conditions or CH_4 (methane) in landfill anaerobic conditions.

Composting

It is one of the forms of biodegradation, where oxygen is continuously available by artificial mechanical means, to rapid the aerobic bacteria's action of breaking down the organic matter. The main gas released in this case after biodegradation is the carbon dioxide, which is often taken as an indicator of biodegradation, when measured in closed lab aerobic biodegradability test conditions. In this applied soil-burial test, carbon dioxide release amounts was not monitored.

Landfilling

Biodegrading in a landfill environment depend mainly on the tendency of organic matter to break down by means of anaerobic bacterial attack without the presence of oxygen or light. This method takes much longer time for the organic matter to break down, and the released methane gas is the indicator of the successful biodegradation in this case.

b. Soil-burial biodegradability test (simulating aerobic compost conditions)

Within this research, biodegradation was investigated, through the studying of the possible attack of aerobic micro-organisms to the RS fibreboards biocomposites produced. The possible aerobic bio-degradability in the presence of oxygen in the soil's upper surface, under around 3 inches (8 cm) deep was investigated; to allow the possibility of living micro-organisms existing normally in the upper surface of normal soils to attack and digest parts of the samples, (Fischer, K.- (iswa)- Fakultät 2- Universität Stuttgart, 2012). Within the industrial scale, anaerobic digestion procedure is the preferred method and most commercial and common one in biological waste treatments, (European Bioplastics e.V., 2011) and (Morse, 2009), due to land limitations and the need of decreasing shallow surface burial methods by replacing them through deeper burial methods, hence preserving the land plots consumed in land filling. But according to this research and within the method of testing, as discussed afterwards, the biodegradability investigation occurred only in aerobic and not in an anaerobic environment, simulating compost conditions in the presence of oxygen and light.

According to (Müller, 2005), a number of biodegradability tests were specified and analyzed including laboratory and field tests, Fig. (C 1-20). Field tests have a number of advantages and disadvantages, including being the most realistic method for determining the possible effect of the aerobic and an-aerobic bacteria of the samples, but at the same time being not a very precise method for biodegradability evaluation, due to many external effects that cannot be controlled unlike the other lab tests. Hence, this applied method reflects and indicates the possibility of the tested materials to be partly degradable under surface soil burial, allowing the aerobic bacteria to have its possible effect on the samples.

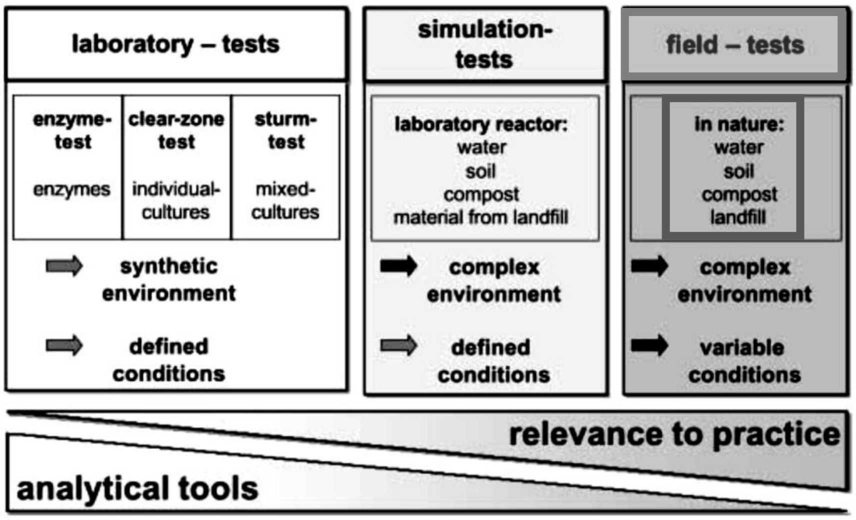


Figure C 1-20. Schematic overview on tests for biodegradable plastics. Photo credit: (Müller, 2005).

According to the standard DIN EN ISO 846 for the determination of micro-organisms reaction on plastics, (Deutsches Institut für Normung e.V. (DIN), 1997), it is recommended to use samples of maximum thickness of 0.5 mm. This condition was not possible to fulfill within this test, hence the same sample's configuration that was applied in all other tests was also applied here, of: 70 x 10 x 2 mm dimensions.

The field test took place in the backyard of the Stuttgart University administration building in the center of Stuttgart city, next to K1-Building of the Faculty of Architecture in Stuttgart - Germany. The total examination time was 15 months, divided into 5 time intervals, each of 3 months. The micro-biological attack was detected through appearance by visual inspection and through weight-loss control. At the end of the test times' intervals, no extra mechanical tests were applied to check if the materials lost their mechanical quality before burial or not. The test procedures are indicated in the following figure, Fig. (C 1-21).

b.1- Test procedures

The test procedures are shortly described as follows:

a. The samples were dried in a drying oven at 70°C for 48 hours and weighed before burial.
b. Within this practical field test of biodegradability simulation, the samples were buried in 5 identical classic PP plastic boxes with big opening, and buried at a level not exceeding of -8 cm under the soil's surface, to allow the reaction of aerobic bacteria, as discussed. For each material, 3 specimens were controlled at each specified time interval.
c. Each box of the 5 identical boxes, containing the tested samples, was picked up after 3 months to analyze the samples and evaluate the changes after this specified time period.
d. The samples were taken from the soil, washed with distilled water and re-dried at 70°C for 72 hours, to guarantee dryness, then moved to a desiccator chamber with a drying agent for 2 hours till they cool down to be ready for weight control procedures.
e. The samples were both qualitatively analyzed, through visual observation, and quantitatively analyzed by comparing the sample weights before and after soil-burial, which was detected through the weight loss percentages within the burial-time.

b.2- Illustration of results

Within 15 months of weight and appearance control after burial, it was found that the samples started losing their weights, as an indication of micro-organisms' attack, already after 3 months of soil burial as indicated in Fig. (C 1-22). It was found that as the RS fibre load increases, the tendency of biodegradability, described in weight loss, is increased. The RS fibreboard of 20% fibre load ([RS (20%) -Vin.]), lost after 3 months already around 5% of its weight, while that 80% fibre load, lost around 20% of its weight. The graph, Fig.(C 1-22), indicates that the [RS (80%) -Vin.] lost around 41% of its weight after 15 months of shallow soil burial, which is an indication of the rapid biodegradability possibility of the produced product. Each 3 months, the samples were photographed, Table (C 1-7). Within the following, a number of samples are visually illustrated to show the micro-organisms' effect on their physical appearances. In addition, this visual inspection indicates how the samples in some cases became a normal part of the soil ecosystem, where roots started growing through the samples' bodies, which were discovered and started to take place after 9 months of soil burial.

Figure C 1-21. Illustration of the soil burial biodegradability test scenario and control procedures

After 3 Months	After 6 Months	After 9 Months	After 12 Months	After 15 Months
				
[RS (80%) -Vin.] almost split, losing ca. 20% of weight	[RS (80%) -Vin.] split into 2 halves and lost ca. 32% of weight	Roots were found growing within [RS (20%) -Vin.] and [RS (40%) -Vin.] samples	Roots were found growing in [RS (40%) -Vin.] and [RS 60%) -Vin.]	[RS (80%) -Vin.] almost split, losing ca. 41% of weight

Table C 1-7. Illustration of the visual appearance changes of the physical state of the samples within 15 months of soil burial

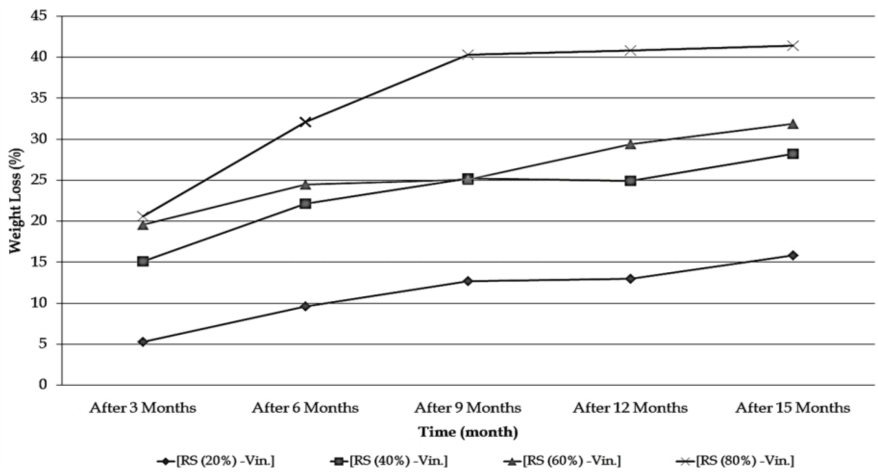


Figure C 1-22. Analysis of the weight loss of the RS elastic probes with different fibre loadings (from 20% to 80%) within 15 months of soil burial

C 1.6. Conclusions

a. The different developed RS fibreboards' properties change greatly, according to the fibre wt. load, which here varies from 20% to 80%. Increasing the fibre wt. load content was a demand and a target to apply the maximum amount of the un-modified fibre load. The cost of the binder applied lies in the same average of the conventional fossil-based polyolefines prices -state 2013, (Weber, K.- Wacker Chemie AG , 2011-2013). Regarding the cheap straw fibre prices as described in Table (A-1), then the economic profit as well as the ecologic one is highly expected from this fibreboard's appliance, especially at high fibre-ratios as here achieved. This would compete with the available wooden and plastic materials applied for the same architectural purposes and available in the contemporary markets. A similar product, which is an elastic board that serves for the same applications' fields of this straw board, is named Recoflex®, composed of wood and cork mixed with latex and polyurethane mixtures ranging from 4-19 mm , (Pohl, C.- Berleburger Schaumstoffwerk GmbH, 2014). The drawbacks of this product, depending on slow renewable and non-renewable resources are eliminated in the developed RS-fibreboards.
b. The developed materials are suggested for interior anti-slip and anti-shock mats for flooring applications, according to the previous illustrated tests and conclusions, and due to the abrasive nature of the naturally existing high silica contents of the pressed raw fibres. In addition, high resistance behavior against collisions and sudden crash loads are also expected, depending on the EVA known performance of resisting collisions, in addition to the high fibre loading (80% that can reach uptill 90% in further developments). Accordingly, this material can suit many flooring applications, especially in interiors. Examples of these applications include interior kids' playgrounds, so as to absorb expected falls, as well as gymnastics and athletic studios flooring, as anti-slip mats, which are typical applications to pure elastic flooring systems. The improved sound pressure resistance is expected to be active at lower fibre loads at (20% and 40%), with the lowest stiffness, which is an important factor in sound transmittance-resistant flooring mats.
c. The elastic performance of the developed board, together with the high density, would enable high quality free-form panels that are suitable for furniture and interior fittings applications, replacing classic wooden HDFs.
d. Fire resistance performance is expected to reach to DIN 4102 -B1 fire class in case of 80-90% fibre load, after adding minimal flame-retardant mineral additives, and can form in

case of extra sealing even better performance together with extra weathering resistance. Resistance towards weathering without edges' sealing was found poor at higher fibre loadings, which indicates that in case of external appliances, the boards should be covered with water resistance foils against direct excessive environmental conditions. Water absorption of [RS (80%) -Vin.] regarding thickness swelling was in a range of (ca. 21%), which is within the accepted range of water absorption ratio within dry manufactured fibreboards (45%), after DIN EN 622-5, and comparable or improved in comparison to previous researches of bleached straw- MDI medium density particleboard developed by (Moa, et al., 2003) and (Halvarsson, 2010).

e. In the diagram, rice straw plant is illustrated as the main source of the production within the biological cycle, indicated in green, according to the cradle to cradle concept, recommended by (Braungart, et al., 2009). It releases the rice straw as a by-product, that transfers as a main resource to be applied in the technical cycle, indicated in blue, for fibreboards' production as here suggested. Applying the selected binder type, allows two end-of-life options of the developed fibreboard to exist. Recycling option should be expected depending on the thermoplastic nature of the selected elastic binder, as well as the ability to biodegrade, as proved in the compost-simulation test applied in this research, to turn back to the biological cycle. This relationship between the two cycles in respect to the proposed material, describing its eco-efficiency, can be described through Fig. (C 1-23).

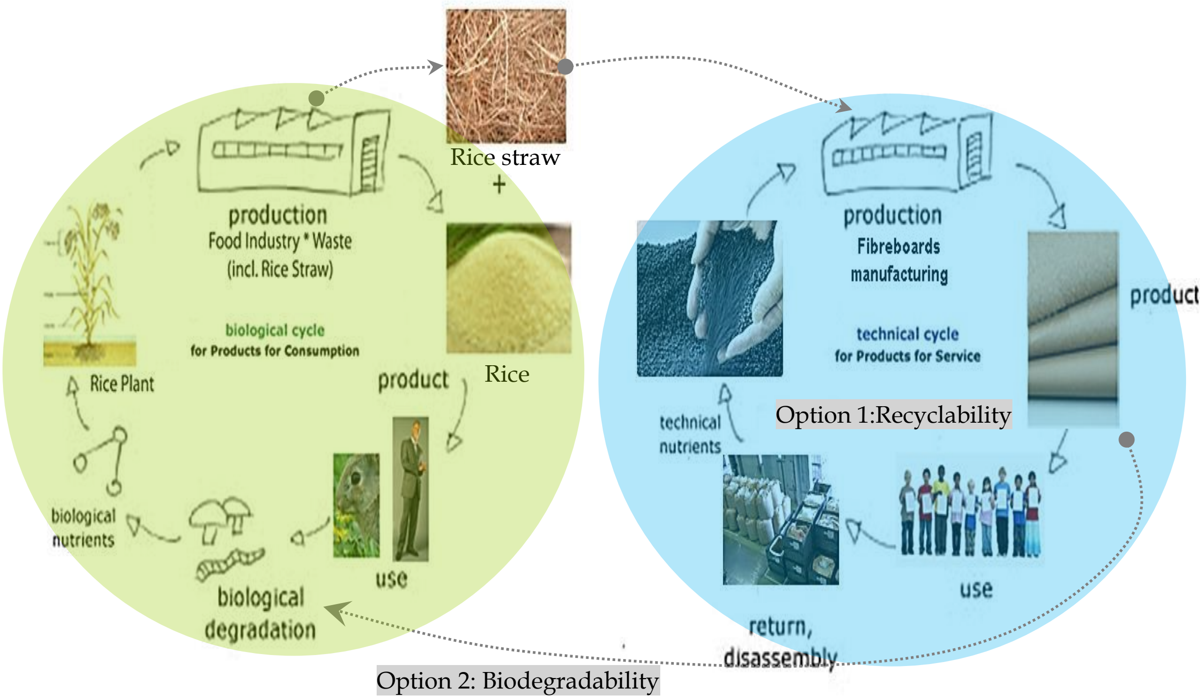


Figure C 1-23. Diagram after the cradle to cradle concept, (Braungart, et al., 2009), emphasizing the environmental assessment of the developed product, according to both its recyclability and biodegradability possibilities discussed

C 2. Green rice straw thermoplastic biocomposites

The main aim here is to develop two types of green RS thermoplastic biocomposites (RS-PLA) and (RS-Lignin), based on RS and bioplastics' combinations, with improved flame-resistance. The green RS agroplastics should offer a lot of ecologic and economic advantages, that are of high value when applied in architectural applications, which is still missing and not available in contemporary markets.

Applying agro-fibres as a flame-retardant is an aspect that was not yet raised in the state of art. Accordingly, within this part two green RS agroplastics are developed and analyzed, regarding mechanical, flame-resistance, water absorption resistance and other technical characteristics. In the following chapter, architectural application possibilities of those developed RS agroplastics will be discussed accordingly.

Through the following parts, the developing process of the green RS agroplastics (RS-PLA) and (RS-Lignin) including the reference RS agroplastic (RS-PP) is illustrated.

C 2.1. Main RS thermoplastic biocomposites' components

Selected agro-fibre: Rice Straw (RS):

Supplied and chopped as previously indicated. Fibre length = (0,5 - 5 mm)

Selected bioplastics binders – for the main green RS agroplastics developemnt

PLA: PLA bioplastic (80 150D) type supplied from Nature Works LLC, USA.

Lignin: Lignin bioplastic Arboform® F45- supplied from Tecnaro GmbH, Germany.

Selected fossil-based binder – applied for comparison

PP: fossil-based virgin PP was supplied form the Institute for Plastics Technology (IKT)- University of Stuttgart, Germany

C 2.2. Comparison methodology

The developed green agroplastics are prepared with 20% wt. RS fibre load: RS 20%wt.-PLA and RS 20%wt.-Lignin.

Properties of RS-PLA is compared to RS-PP at the same fibre load (20%). In this case the binder was changed while the fibre type and filling ratio kept the same.

Properties of RS-Lignin is compared to Cellulose-Lignin at the same fibre load (20%). In this case the binder was the same as well as its filling ratio, while the fibre type changed.

The reason for these differences in comparison criteria is that pure PLA characteristics is known to be comparable to polyolefines including PE and PP, and can replace it in its applications; while lignin bioplastics has no specific fossil-based thermoplastic to be compared with as in the case of PLA and PP. Therefore, it was settled to keep the natural fibre load the same in all cases, and compare the properties of the developed green RS agroplastics as follows:

Green rice straw thermoplastic biocomposites and comparison methodology

TARGET: Green rice straw thermoplastic biocomposite		Developed biocomposite for comparison	
RS -	**PLA**	**RS -**	**PP**
20%wt.	Biomass-based bioplastic	20% wt.	Fossil-based plastic
TARGET: Green rice straw thermoplastic biocomposite		**Developed biocomposite for comparison**	
RS -	**Lignin**	**Cel-**	**Lignin**
20%wt.	Biomass-based bioplastic	20% wt.	Biomass-based bioplastic

To validate the developed green RS agroplastic composites' possible market presence, a green thermoplastic biocomposite material of (cellulose-lignin) basis was selected from the contemporary market and compared with the developed composites. The market product is referred to as (Market- Ref.) in the following text and analysis. The (Market- Ref.) was cut into the same specified specimen's dimensions and tested in the same applied conditions as other specimens.

C 2.3. Compounding process and specimens preparation

C 2.3.1. Green biocomposite 1: RS-PLA

The previously mixed RS-PLA at 20%fibre load wt. was pre-mixed at room temperature then supplied into a lab-scale twin screw extruder, supplied from the Fraunhofer Institut (ICT) in Karlsruhe.

The machine was heated differently in a gradual manner at the 5 heat canals within the extruder, where the first one that directly follows the feeding opening was settled at 150°C, then the following 3 canals were settled at 160°C and the third one was heated by 170°C, while rotation speed was fixed at 72 rpm (rotation/minute).

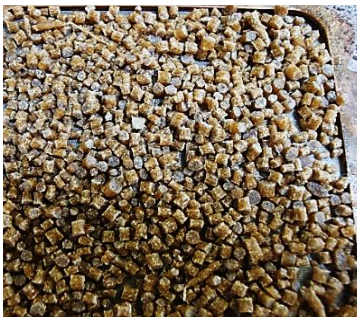
After the compounding process took place, the RS-PLA composite thread was pulled out to cool down, before being cut into granules that were afterwards packed, Fig. (C2-1), to be later heat-pressed in a separate process through a lab-press machine.

The pellets were pressed at 190 °C for 5 minutes, to formulate the plates, which were cut afterwards into the specified specimen dimensions: 70x10x2 mm.

1-The RS-PLA were pre-mixed before dosing the mixture in the extruder

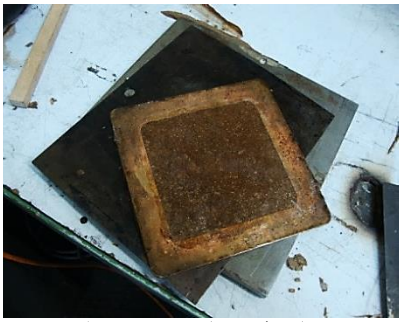
2-Applying the prepared mixture within the extruder

3-RS-PLA thread after being compounded and extruded from the extruder's nozzle



4-The RS-PLA pellets before being pressed in the heat-press machine

5-The pellets in the copper mold, covered by the Teflon® foils, before being pressed



6-The RS-PLA plate after being thermally pressed

Figure C2-1. RS-PLA biocomposite manufacturing process

C 2.3.2. Green biocomposite 2: RS-Lignin

The compounding took place using a twin screw extruder machine supplied by Tecnaro GmbH. The straw was applied to the pure lignin pellets without other fibre type incorporation. The supplied bone shaped specimens were further cut into the pre-specified specimen dimensions as other specimens.

C 2.3.3. Reference biocomposite 1: RS-PP

The compounding took place using the same batch mixer, 'HAAKE Rheocord 90', supplied from IKT-University of Stuttgart. The machine was pre-heated at 180°C and the screws' revolving velocity was settled at 20 rpm (rotation/minute).

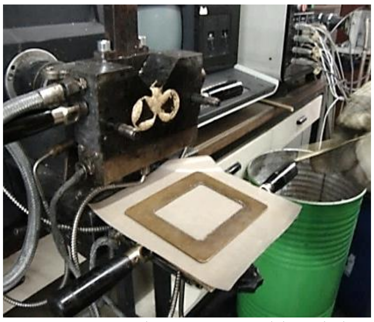
The dosing procedures of the 20%wt- RS was gradually applied in successive phases with PP, where PP was the first to be dosed in the compounding process and the last to end the process with, to obtain a homogenous mixture.

The feeding process took around 3.5 minutes and the mixture was left for extra 5 minutes to complete mixing. After the compounding process took place, the discharge was taken and immediately heat pressed with the laboratory bench-top press-machine (Type P 200 E) from Dr. Collin GmbH- Ebersberg, Germany, 190°C degrees at 100 Bar for 1 minute. Then the resulted plates were cut afterwards in the same settled specimen size.

1-The chopped straw and PP before the dosing takes place.

2-Dosing a small quantity of straw as a second process after PP.

3-The mixture of straw and PP in the batch mixer, before taking out the discharge



4-Preparing the copper mold and the Teflon® sheets to place the composite's discharge on it to be hot pressed afterwards

5-RS-PP Composite before being pressed in the hot-press machine

6-The plate produced with the excess wedges before being cut out

Figure C 2-2. (RS-PP) biocomposite manufacturing process

C 2.3.4. Reference biocomposite 2: Cellulose-Lignin (Cel.-Lignin)

Cellulose fibres of hemp and cotton mixed with lignin at 20-30% fibre weight, was supported in bone-shaped specimens from Tecnaro GmbH, which was also cut as specified.

C 2.4. Developed green RS thermoplastic biocomposites - Properties analysis

C 2.4.1. Density

The densities were measured according to DIN 53 479 or DIN EN ISO 1183-1, (DIN e.V.: Deutsches Institut für Normung e.V., 2013), standard of density measurement in the labs of IKT-University of Stuttgart at 23 +/- 1 °C. Applied chopped straw in its raw form is of average 40-100 Kg/m^3, after (Jenkins, 1993). Densities of developed materials are displayed as follows:

Biocomposites' Groups	**RS-PLA**	**RS-PP**	**RS -Lig**	**Cell. -Lig**
Fibre type and wt. %	RS - 20 %	RS 20 %	RS 20 %	Cell. 20 %
Density [g/cm^3]	1,2320	0,8883	1,3355	1,310

Table C 2-1. Densities of the developed biocomposites

As displayed, the RS-PLA composite is denser than RS-PP that shares the same fibre load (20 %), while RS-Lig composites recorded higher densities than the other compared materials.

C 2.4.2. Water Absorption

The samples were dried at 50±2°C for 24±1 hours, then were laid into a desiccator with a drying agent to cool down before being weighed. The samples were then immersed in distilled water for 24±1 hours, after DIN EN ISO 62- 2008, (DIN Deutsches Institut für Normung e.V. , 2008). The weight differences were recorded with a with ± 0,1 mg weighing device. Generally, water absorption's value identifies the fibre-matrix interface's efficiency.

Biocomposites' Groups	RS-PLA	RS-PP	RS -Lig	Cell. -Lig
Fibre type and wt. %	RS - 20 %	RS 20 %	RS 20 %	Cell. 20 %
Water Absorption [%]	4,6	1,8	8,9	4,8

Table C 2-2. Water absorption in % of the developed biocomposites

According to Table (C 2-2), it is clear that generally, green RS thermoplastic composites are more sensitive to humidity than RS-classic plastic composites, represented in RS-PP. Within the developed green composites, RS-PLA has shown more resistance to water absorption than RS-Lignin. The (RS -PLA)'s water absorption was lower than the (Cell.- Lig.).

As seen in Table (C 2-3), through optical inspection of the two developed green composites (RS-PLA) and (RS - Lig.), the color change of the water in case of (RS –Lig.) is observed, which indicates the tendency of the material to be dissolved easier in water than (RS-PLA). That's why the (RS-Lig.) material should be applied in indoor dry applications. In addition, small bubbles were observed on the surfaces of (RS-PLA), which indicates the presence of small holes on the samples' surfaces.

Biocomposites' Groups	RS-PLA	RS -Lig
Photo after 24 hours of samples' immerse in distilled water		

Table C 2-3. Photos illustrating the optical examination of the green composites' samples in water after 24 hours of immersion

The difference in the absorption attitude between the developed (RS -Lig.) and (Cell. -Lig.)and (Market-(Ref.)) was surprisingly great, although they share the same binder-base, lignin, and similar lignocellulosic natural fibre-base. It is accordingly obvious that the later market material, (Market- (Ref.)), includes much higher additives' contents and much lower lignin matter than that of the developed composite (RS - Lig.).

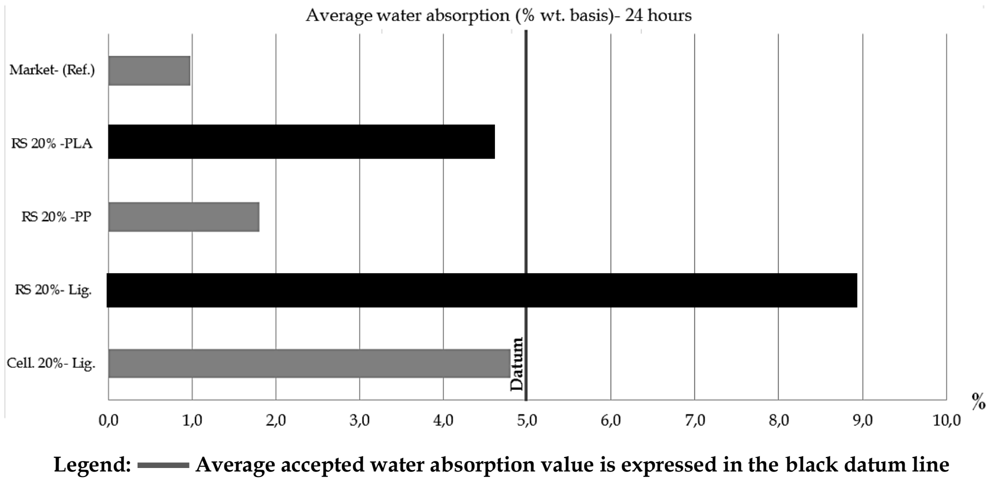


Figure C 2-3. The mean value of water absorption for the developed green RS thermoplastic composites, reference biocomposites and the selected market product.

According to (Gerth, 2013), in Magdburgh, Germany, the average accepted water absorption sensitivity for biocomposites lies below or equal to 5 %. Ideally, according to (Azwa, et al., 2012 p. 427), the typical water gain in biocomposites after 24 hours of water immersion lies between 0.7-2 %. RS-Lig was found to be extra sensitive to humidity, recording more than 8 % of water absorption, while RS-PLA was found more resistant to water absorption.

C 2.4.3. Mechanical Properties

E-Modulus and tensile strength properties

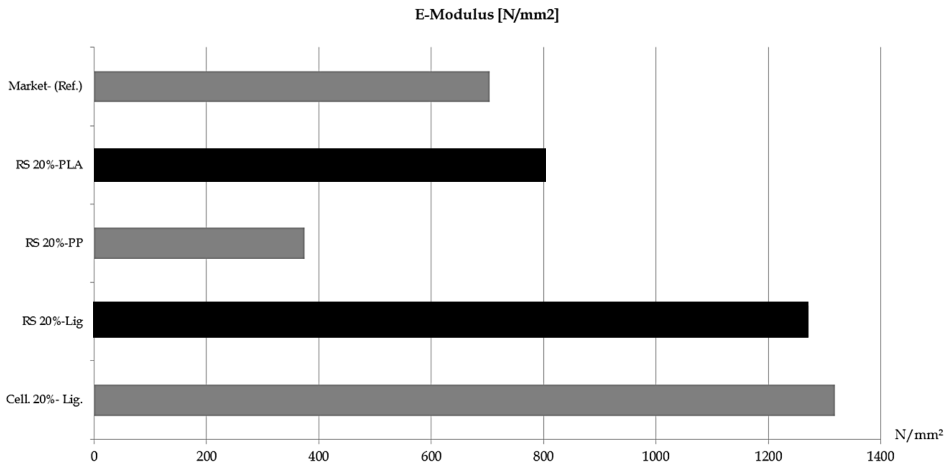


Figure C 2-4. Illustration of the developed green biocomposites' elastic modulus, representing the tensile stiffness or resistance to deformation, in comparison to RS-PP and Cel.-Lig. at same fibre load of 20%-wt, and a market material

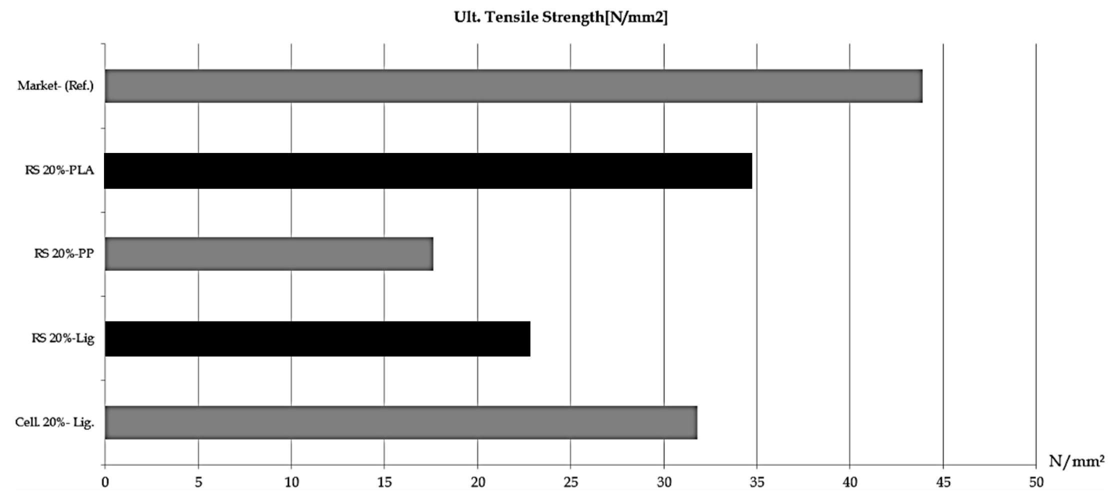


Figure C 2-5. Illustration of the developed green biocomposites' tensile strength, in comparison to RS-PP and Cel.-Lig. at same fibre load of 20%-wt, and a market material

Discussion

It is obvious that the green biocomposites enjoyed better tensile strength properties than that of the (RS- PP) composite, at the same fibre ratios (20 %wt.). This reflects the influence of the better bioplastics properties, in addition to the better compatibility of RS as a natural raw fibre with its same family-derived polymers.

Both developed materials, (RS-PLA) and (RS-Lig.) have shown higher or equal stiffnesses in comparison to the reference market material (Market-(Ref.)). However, lower tensile strengths were recorded in both cases.

(RS-Lig.) has higher tensile stiffness and is more brittle than (RS-PLA) and (RS-PP) and is almost equal to (Cel.-Lig.). On the other hand (RS-PLA) enjoyed high tensile stiffness in comparison to the (Market-(Ref.)) and the developed (RS-PP), and higher tensile strength properties than that of (RS-Lig.) These remarkable mechanical properties of (RS-PLA) and (RS-/Lig.) in comparison to (RS-PP) should enable them to replace the later in different architectural applications.

C 2.4.4. Morphological Examination

The samples were examined at the fracture surface of the torn-out samples resulted from the tensile test using a scanning electron microscope (SEM), supported from the IKT- University of Stuttgart, to have a better understanding on the relationship between the raw milled straw and the bioplastic, in the case of the developed green composites: (RS-PLA) and (RS-Lig.), to distinguish how homogenous and compatible they are, and how this might affect the material properties.

The samples' examination photos are illustrated through the following tables, accompanied by discussion and analysis:

a. Surface Morphology

Through the following table, surface morphology is illustrated. As seen, (RS- PLA) surface seems much more 'sealed' than that of (RS- Lig.). That is why (RS- PLA) resistance towards water absorption was much higher than the other biocomposite as previously illustrated.

The swelling could be much improved if the surfaces were much better sealed by the polymer in case of PLA. On the other hand lignin seems to have problems with its structure when injected, obtaining 'un-closed' surface. This is believed to be due to the low viscosity of the mixture that lead to the slow flow within compounding, which caused the polymer not to be able to flow properly and close the surface layers.

This problem could be more effective during the composite's cooling phase after injection, leading to these opened gaps on the composite's surface, subjecting it to be easily attacked by the water's molecules that enter easily through the composite's body through these surface gaps, causing quick swelling.

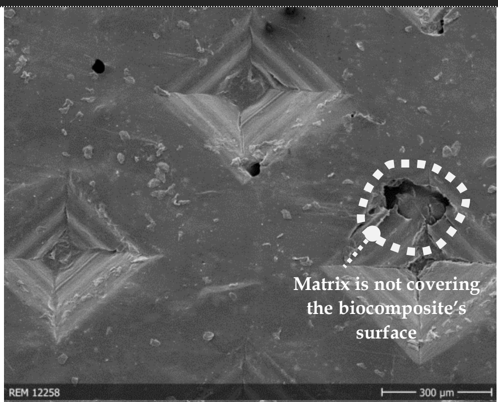
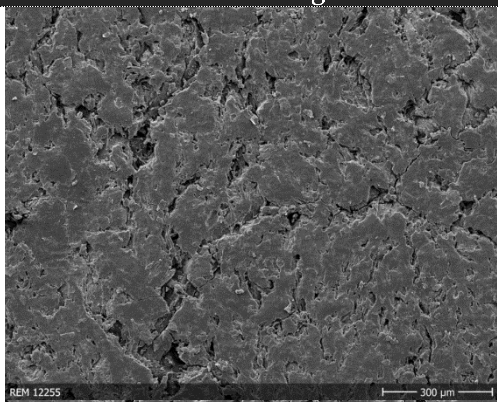
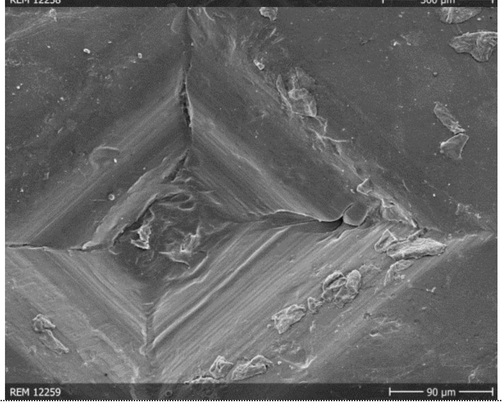
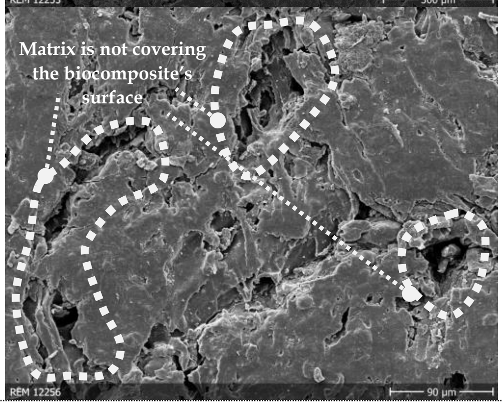
RS 20 %-PLA	RS 20 %-Lig
	
	

Table C 2-4. Comparison between (RS 20% -PLA) and (RS 20 % -Lig.) surface morphology using SEM-microscopic analysis

b. Cross-section Morphology

Through the following table, the homogenous distribution of the fibre and its interface relationship with binding material is illustrated. It is clear through this microscopic examination that the (RS- Lig.) mixture and interface is much more homogenous than that of (RS- PLA).

The compatibility and the harmony found between the fibre and the polymer in case of (RS -Lig.) as well as the fibre direction control and equal distribution throughout the compound is also clear through the illustrated microscopic examination.

RS-PLA fibre/matrix interface was not found optimum. This is clear from the dark voids surrounding the fibre in the second photo. However, it is clear within the same photo and in the last one that other free-oriented fibres were strongly bonded with the polymer, as they protruded out of the broken profile. The strong fibre/matrix interface in case of (RS-Lig.) enabled the composite to have high tensile stiffness and resistance to deform as pre-illustrated within the applied uni-axial tension test.

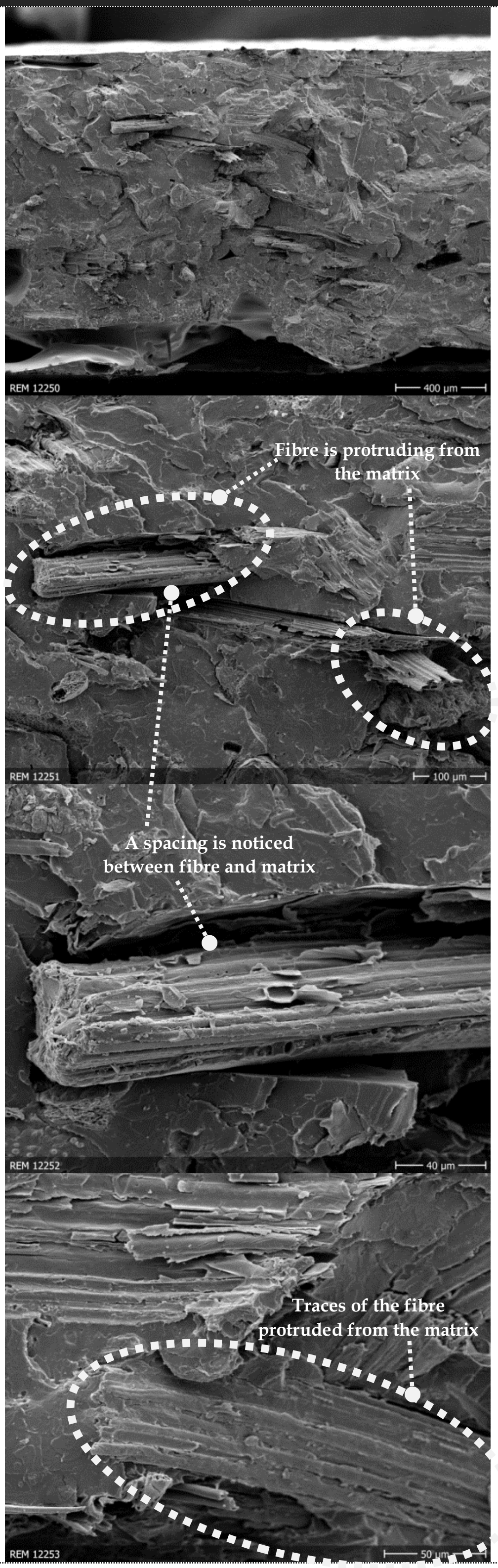
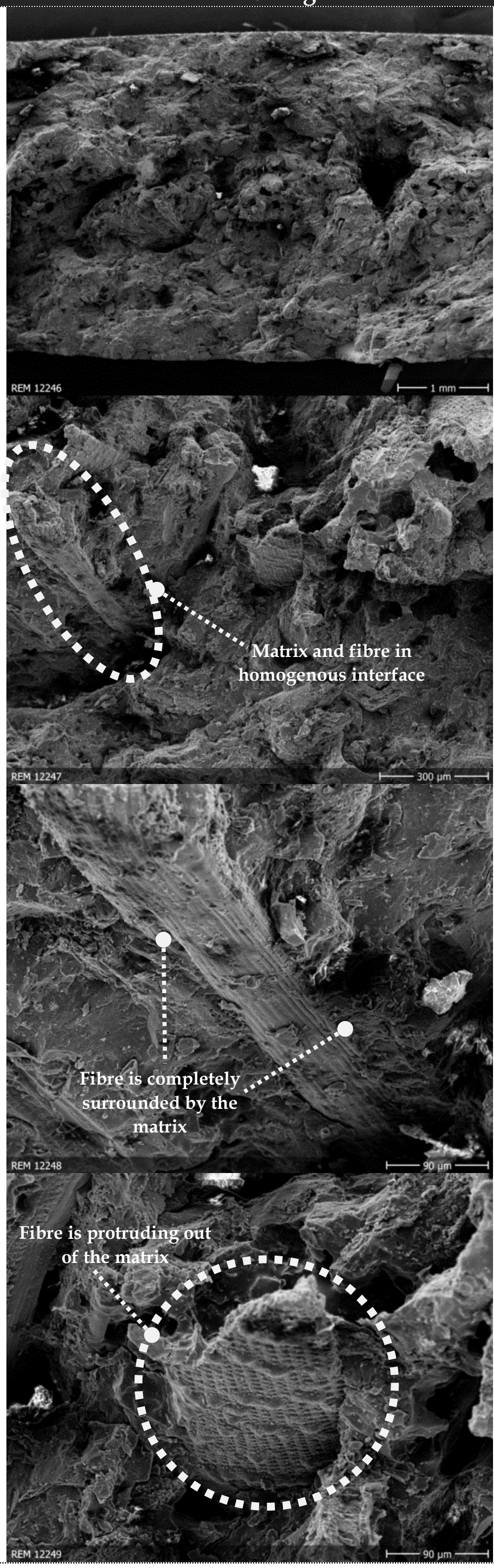
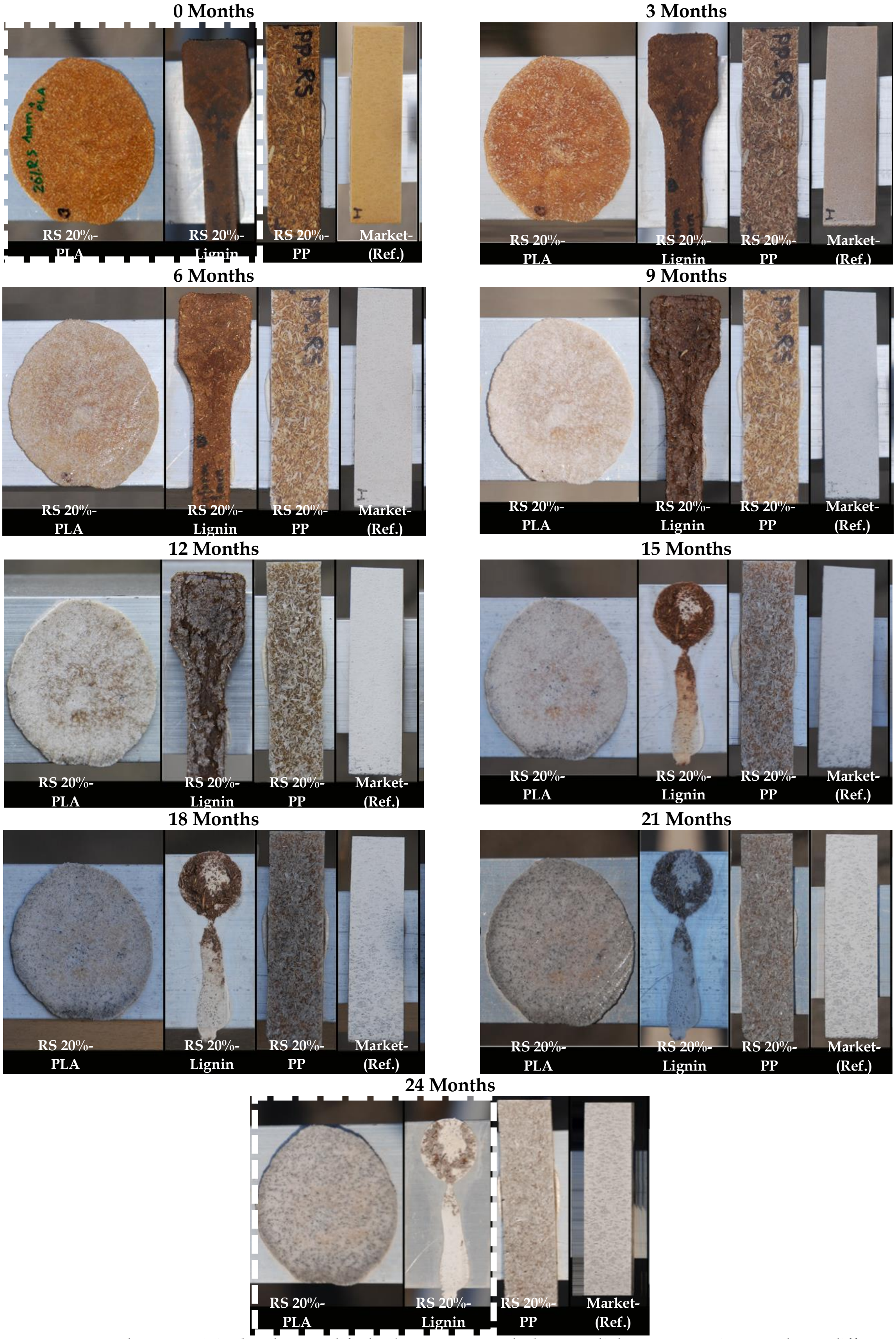
RS 20 %-PLA	RS 20 %-Lig
	

Table C 2-5.Comparison between (RS-PLA) and (RS-Lig.) cross-section morphology using SEM-microscopic analysis

C 2.4.5. Free weathering



Note: apparent colors are original and un-modified colors. Any extra darkness or lightness appearing was due to differences in natural lighting within different weather seasons and climate differences.

Table C 2-6. Visual comparison of the appearance changes, during 24 months of free-weathering, of the developed biocomposites and the market reference

Test evaluation and discussion

As previously illustrated, it is clear that the developed green biocomposites (RS-PLA) and (RS-Lig.) are much affected by humidity and biological attack than the (RS -PP) biocomposite. The market cellulose-lignin based material (Market-Ref.) had almost the same effect as (RS-PP), which indicated that the lignin's percentage in this material is not high enough as in the case of the developed (RS-Lig.) biocomposite.

Generally, all materials whitened by the end of the 24 months including (RS-PP). (RS -Lig.) recorded the worst UV and weathering resistance within all tested specimens, since it started weathering-out after only 1 year of free-weathering. The sample flew away as its particles became no more rigid enough to complete sticking to the rack's surface, so the sticking material applied is seen clear on the rack instead. In this research, the specimens were not mechanically tested after the weathering took place to monitor the possible loss in the mechanical quality of the developed biocomposites. However, for future work, it is recommended to measure the specimens' technical properties, from which mainly are the mechanical properties, after the free- weathering test.

C 2.4.6. Flammability Behavior

The samples were tested for their flammability behavior according to the UL 1694 as previously indicated. The burning time applied on the specimens were 20 seconds, according to the volume of the specimens applied, and the timing after flame application till the flame ceased was recorded (t_{b1}). In some cases, the flame ceased shortly after flame application, so the flame was directly re-applied for the same time interval that was applied at the beginning till the second flame ceased as well and stopped flaming or glowing, which is the after flame time that was recorded as well in seconds (t_{b2}). The same previous step would be repeated if the sample was not yet consumed and the after flame time, after the third ignition, was recorded in seconds (t_{b3}).

The effect of the high silica contents present in the applied raw rice straw, on the flammability attitude of the developed biocomposites were here evaluated. The non-presence of additives enabled the objective comparison to take place, eliminating the presence of extra factors that could have caused evaluation mistakes.

Test results and evaluation

Biocomposites Groups (at 20 % RS wt.)	**RS 20 %-PP (Reference)**			**RS 20 %-PLA**		
[sec.]	$t_{b\,1}$	$t_{b\,2}$	$t_{b\,3}$	$t_{b\,1}$	$t_{b\,2}$	$t_{b\,3}$
Spec.1	105	0	0	3	15	0
Spec.2	112	0	0	2	58	0
Spec.3	148	0	0	2	35	85
Spec.4	110	0	0	3	41	50
Spec.5	115	0	0	4	50	0
Cotton Indicator Ignition (Yes/No)	**Yes**			**Yes**		
Complete consumption of specimen (Yes/No)	**Yes**			**2 samples: Yes, 3 samples : No**		

Notes	**The samples were completely consumed and took >100 sec. till the flame reached the clamp and the burning stopped. The samples' test results described a material, which is below standards and cannot be specified accordingly to a certain material class.**	**A part of the sample did not burn in 3 tested samples. The sample's ignition stopped after <5 sec for all samples, and the second ignition stopped after <60 sec. for all samples. However the developed material did not have a specific material class, but was closely equivalent to UL1694-TC-2**

Table C 2-7. Illustration of the flammability attitude of the (RS 20% -PP) and (RS 20 % -PLA) after UL1694.

As recorded in the tables (C 2-7) and (C 2-8), it can be concluded that the natural silicate contents in the RS tissues had its great effect as expected, especially when compounded by bioplastics much more than fossil-based ones.

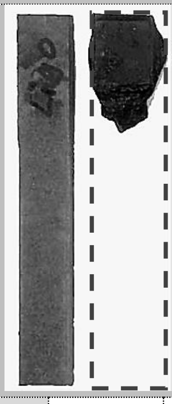
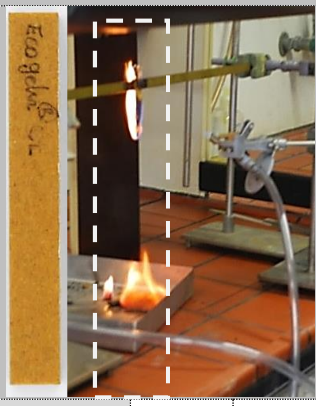
Biocomposites' Groups (at 20 % RS wt.)	**Cell. 20 % -Lig**			**RS 20 %-Lig**			**Market-Ref.**		
Photo									
[sec.]	$t_{b\,1}$	$t_{b\,2}$	t_{b3}	$t_{b\,1}$	$t_{b\,2}$	t_{b3}	$t_{b\,1}$	$t_{b\,2}$	t_{b3}
Spec.1	15	152	0	7	30	7	80	0	0
Spec.2	12	166	0	5	30	10	92	0	0
Spec.3	20	120	0	6	28	8	55	0	0
Spec.4	17	142	0	8	32	12	155	0	0
Spec.5	19	130	0	5	27	5	119	0	0
Cotton Indicator Ignition (Yes/No)	**No**			**No**			**Yes**		
Complete consumption of specimen (Yes/No)	**Yes**			**No**			**Yes**		
Notes	**The initial after ignition time was >10sec, but less than 30sec. $t_{b\,1}$+ t_{b2} were together <250sec. $t_{b\,2}$+ t_{b3} were together >60sec. The cotton indicator was not ignited and the samples were totally consumed. Accordingly, the material did not belong to a specific material class according to UL 1694.**			**The first after flame time was <10sec, while $t_{b\,1}$+ t_{b2} were together <50sec. $t_{b\,2}$+ t_{b3} were together <60sec. In addition, the specimens weren't consumed and there were no droplets on the indicator. Accordingly, the detected fire class was UL 1694 SC-1**			**The samples were completely melt to the clamp, and consumed after the first ignition in more than 30 seconds, which is the time considered according to the standard applied. Hence, the material is below the applied standard and can not be ranked under a specific material fire class.**		

Table C 2-8. Illustration of the flammability attitude of the (Cell. 20 %-Lig.), (RS20 %-Lig.) and market reference material after UL1694.

This RS-bioplastic interaction led to changing the flammability behavior (RS20 %-PLA), with only 20% fibre filling load by weight, while (RS20 %-PP) was completely melt down and kept burning without self-extinguishment till the clamp.

(RS-Lignin) combination was more successful, probably due to the special relationship between the silica and straw lignin present together in a special combination in the RS structure, as recorded by (Jiang-yu, et al., 2006) in China.

This is believed to increase the compatibility and extra effect of this odd and special silicate-lignin effect when combined with refined lignin plastic as a binder, which gave the silica the chance to precipitate properly and homogenously through the composite's structure, having then enough chance to optimize the fire-resistance effect as recorded.

The fire class of (RS-Lig.) was recorded UL 1694 SC-1, when straw replaced cotton and hemp fibres in (Cell.-Lig.), which lied beyond the material classification of the applied UL1694 test. It is believed that in case of applying DIN 4102, RS-Lig. would reach B1 and RS-PLA would reach B3 as discussed in (Dahy, 2014).

In a previous research, lignin isolated from straw, through soda-pulping process, was applied in the form of a thermoplastic applied by (Guigo, et al., 2009) , in collaboration of silicate clays, where sepiolite (magnesium silicate) and organically modified montmorillonite (Org-MMT) were separately applied to the straw- based lignin reinforced with natural fibres, to improve the thermal behavior and fire-resistance. The outcome revealed that the Org-MMT-based lignin products have shown improvement in the thermal behavior of the green biocomposite, suggesting a new era in the lignin-based nanocomposites, depending on more ecological additives instead of the halogen-flame retardants with their environmental concerns.

Through the RS's application as a flame-retardant as discussed, and through the illustrated test results, it can be deduced that RS - the cheap available fibre- should play the same role of the silicate clay, that was previously trialed in the last mentioned research work, with much higher ecologic and economic influence. This aspect is of crucial importance in constructional and architectural applications.

C 2.4.7. Environmental assessment with respect to recyclability and biodegradability

The developed green RS-bioplastics can be recycled, and/or incinerated for energy recovery. An extra material's recovery option is the ability to be safely composted and returning back to the eco-system through breaking down by means of micro-organisms and returning back to the soil. Soil burial test was applied to prove this, and the observatory results, as well as the quantitative analysis, are described through the following tables:

Visual Comp.					
Time / Weight decrease (%)	After 3 Months	After 6 Months	After 9 Months	After 12 Months	After 15 Months
RS 20 %-PLA	2.0788	4.236	4.573	5.07	5.144
RS 20 %-PP	1.424	2.244	2.527	3.597	3.661

Table C 2-9. Comparison between (RS-PLA) and (RS -PP) at fibre load of 20 % wt., visually and quantitatively through weight loss

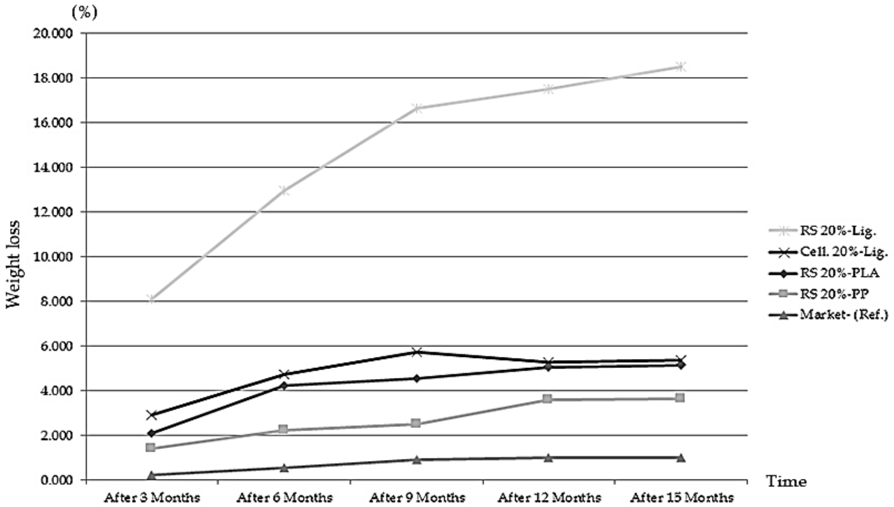
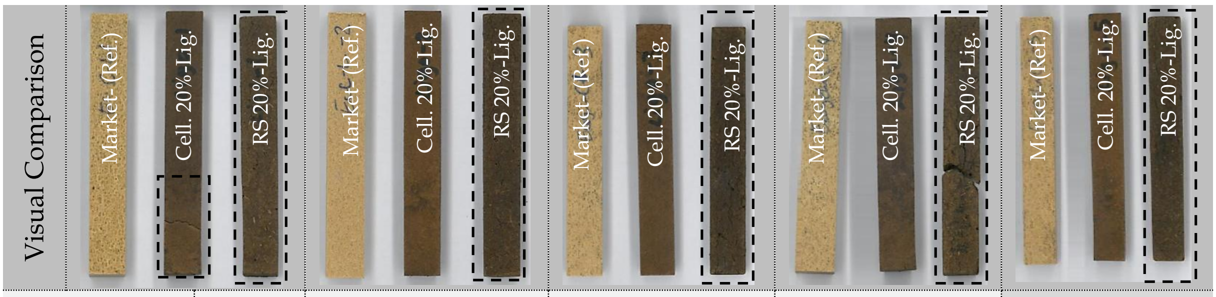


Figure C 2-6. Graph illustrating the weight loss of the developed green RS biocomposites in comparison to the chosen references

Through Table (C 2-9) and Fig. (C 2-6), it is clearly revealed that (RS-PLA) group was resistant enough against biological attack, whether through visual inspection or through analytic weight loss comparison. (RS 20 %-PP) showed less weight loss than (RS 20 %-PLA), but still both lied in the same range of 5 % even after 15 months of soil burial. This was un-expected for the (RS-PLA) group. This indicates that RS-PLA won't be readily biodegradable at the end of its useful life time, and that it would need special compost conditions like extra heat and pressure to decompose.

Through Table (C 2-10) and Fig. (C 2-6), it is clear that (Market-(Ref.)) material has recorded the least weight loss in all handled biocomposites. This indicates again that the lignin percentage in this composite is not high enough in comparison with (Cell. - Lig.) and (RS-Lig.). (Market-(Ref.)) material started slightly degrading after the first 3 and 6 months, then the weight loss kept stable till the end of the 15 months recording around 5 %, comparable to (RS -PLA). (RS - Lig.) has recorded directly after the first 3 months the highest degrading rate, recording around 8 % of weight loss, and this weight loss kept increasing simultaneously with time till it lost around 18 % of its original weight at the end of the 15^{th} month of the defined test period.



Time / weight loss (%)	After 3 Months	After 6 Months	After 9 Months	After 12 Months	After 15 Months
RS 20%-Lig.	8.079	12.949	16.652	17.517	18.508
Cell. 20 %-Lig.	2.916	4.725	5.74	5.278	5.386
Market-Ref.	0.252	0.570	0.928	0.991	1.007

Table C 2-10. Comparison between (RS 20%-Lig.) ,(Cell. 20%-Lig.) and Market-Ref., in respect to the ability to be aerobically compostable qualitatively and quantitatively

Visually, the (RS 20 %-Lig.) had obvious cracks in the sample's structure, and was even split into 2 parts after 12 months. On the other hand, (Cell. 20 %- Lig.) as a reference material was much stable and had almost no observatory cracks on its surface, except for one of the samples directly after the first 3 months, as shown in the previous table.

C 2.5. Conclusions

Developed biocomposites	RS 20 %-PLA	RS 20 %-PP	RS 20 % -Lig.	Cell. 20%-Lig.
Fibre Price	- -	- -	- -	++
Polymer Price	1.2 x	x	1.9 x	1.9 x
Mechanical properties	+	-	++	++
Water Absorption	+ -	+	- -	+-
Compatibility/Morphology	+	-	++	++
Fire Resistance	+	- -	++	+
Natural weathering	-	+	- -	- -
Biodegradability	-	- -	++	+

Legend: - : low/ bad/ un-reasonable , + : high/good/reasonable

Prices comparison are symbolized after regarding contemporary prices of PLA (Grande, J.A.; Plastics Technology Magazine, 2007), PP (Plastics Technology Magazine, 2011) and Lignin (European Commission, 2013)

Table C 2-11.Comparison between the technical properties and prices of the developed biocomposites

Through the previous table, it is clear that green lignin-based biocomposites would cost the highest in comparison to other biocomposites, while (RS-PLA) and (RS-PP) difference should be much narrowed in the near future according to the continuous price-gap shrinkage between PLA and PP with time, according to (Endres, 2012 p. 100).

(RS 20 %-PP) had the lowest density within the developed composites, while (RS20 %-Lig.) and (RS 20 %-PLA) enjoyed much higher densities. Through the tension tests' results, it was clear that both (RS-PLA) and (RS-Lig.) do enjoy much higher tensile strengths and elastic modulus (E-Modulus) than that of (RS-PP), indicating the high possibility of replacing the similar applications of the conventional agroplastics with fossil-based thermoplastics in the market. However on the other hand, the 24 hours-water immersion test revealed that green biocomposites still suffer from higher water absorption in comparison with (RS -PP). The worst water resistance was resulted from the (RS-Lig).

Concerning homogeneity and compatibility, (RS-Lig.) biocomposite has shown higher compatibility with the applied agro-fibre than that of (RS-PLA). This was clear through both the morphological SEM examination and the fire-test results. Both examinations revealed the high flame-resistance of the (RS-Lig.) in comparison with the other developed biocomposites, assuring the first suggested hypothesis that stated that the compatibility of the inner silica/lignin contents of the rice straw and the lignin thermoplastic binder were expected to be high.

Accordingly, RS's collaboration with lignin bioplastics resulted in changing the whole material fire class of the applied in comparison with (Cell.-Lig.), when RS replaced the natural cellulose fibres bonded by lignin.

When (RS 20 %-PLA) and (RS 20 %-PP) were compared, (RS 20 %-PLA) has shown surprisingly as well much better fire performance than that of RS-fossil-based plastic combination. This indicates the possible normal compatibility between the natural bio-based polymers and the selected natural fibre much more than that with the synthetic one.

Regarding biodegradability, (RS-PLA) has shown surprisingly much higher resistance towards degradation, both visually and analytically through weights' comparisons after and before burial. However, the resistance towards biological attack was not high when the same material was subjected to natural weathering for almost 2 years. The material was whitened and with time and severe normal weathering conditions, the materials' edges started to decay, especially after the first year.

RS-lignin composite has shown the worst resistance to normal weathering, as the sample even flew-away before the end of the second year of the weathering test. (RS 20%-Lig.) has also shown tendency to rapidly degrade within the biodegradability soil-burial test as its weight decreased simultaneously with time increase, reaching 18.5 % of weight reduction after 15 months of soil burial, as a result of aerial bacterial attack.

Generally, it can be concluded that (RS-PLA) and (RS-Lig.) can replace natural fibre- fossil-based binder combinations, that are widely spread in architectural interiors. Future investigations should take place to improve the water resistance of the developed green RS-biocomposites. It is expected for the (RS-PLA) composite to enjoy more recycling cycles than that of (RS-Lig.), for its relative decomposition-resistance, which was clear within the biodegradability test.

It is recommended for future work to apply coupling agents to improve the fibre/matrix interface to improve the mechanical properties of the developed composites. In this case, fire behavior should be once more tested and evaluated if the behavior of the green composites would change due to the compatibilizers' presence or not. It is also recommended to test the mechanical behavior of the materials after the free-weathering test, to monitor the possible mechanical properties' loss.

C 3. Green rice straw thermoset biocomposites

In the state of art, it was declared that green agro-fibre thermoset biocomposites do not yet exist in the contemporary market, while green industrial natural fibre thermoset biocomposites based on hemp, flax and others, exist in rare applications in the building industry. In this context green RS thermoset biocomposites are here developed to win another type of cheaper ecological friendly materials that are suitable for more design options that can not be offered by the former developed green RS agroplastics, including exterior architectural applications.

In this part, two green RS thermoset biocomposites are developed, using two types of available bio-epoxy resins in the local European market. The specimens are prepared by combining only 20%wt. of RS-fibre, to be able to compare it afterwards with the former developed green RS-thermoplastic biocomposites described previously in this chapter. However, within the following chapter, a number of prototypes of the same selected agro-fibre, RS, was manufactured according to special product-designs, but with much higher fibre load wt. which reached 50%, as described afterwards.

Within this part, three biocomposites were prepared, where two of them are green RS-bio-epoxy resin biocomposites, as indicated, and the third is a RS- fossil-based epoxy resin for comparison. The three biocomposites were prepared using the same RS fibre load (20% wt.) and the same fibre length (0,5 - 5 mm)

C 3.1. Main green RS thermoset biocomposites' components

a. Selected agro-fibre: Rice Straw (RS):

Supplied and chopped as previously indicated. Fibre length = (0,5 - 5 mm)

b. Selected bio-epoxy binders – for the main green RS thermoset biocomposites developemnt

b.1- PTP®:

A plant oil-based epoxy, provided from B.A.M. (Bio- Composites and More GmbH), Germany. It is prepared from a mixture of 3 components A, B and C Components; where (A) is the bio-based epoxy resin derived from plant-oil basis of concentration 55-65%, (B) is the hardener of concentration 35-45%, and Component (C) is the additional PTP accelerator (concentration 2.5-5%) which is only activated by heat. The plant oil (e.g. linseed) is transformed to epoxidized triglycerides that are combined with polycarboxylic acid anhydrides (based on bio-ethanol) and an initiator, as declared in the following figure. This compound was only activated by heat (ca. 130° C) for ca. 45 minutes to polymerize. Therefore, the mold was composed of flat metal plates.

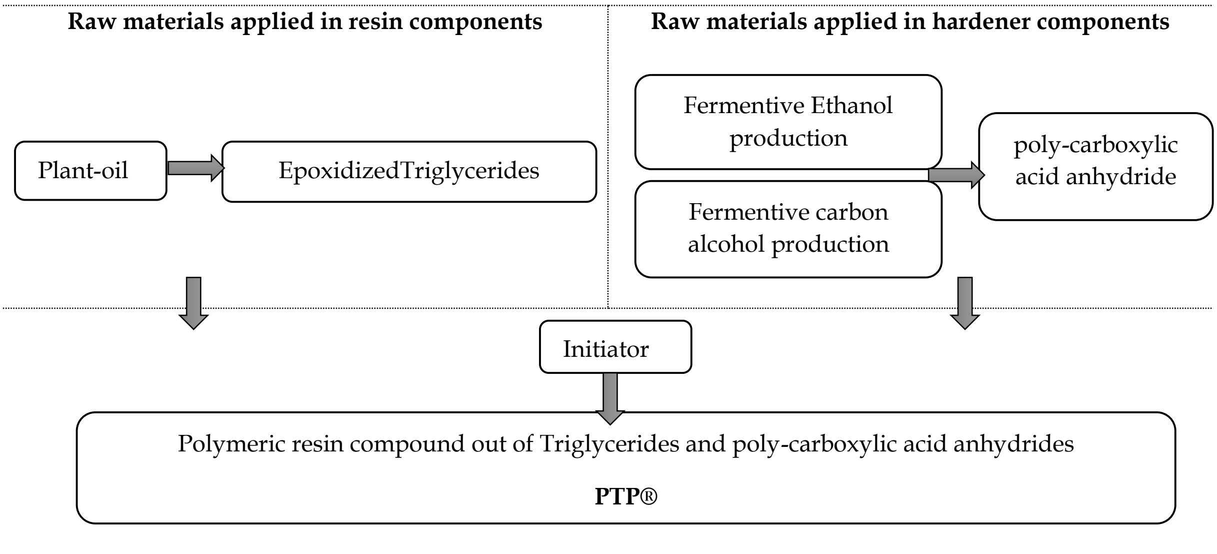


Figure C 3-1. Illustration of the main components and manufacturing hierarchy of the PTP® bio-epoxy resin applied, after (Schönfeld, 2000) and (Müssig, 2001).

b.2- Gripox®:

A bio-based epoxy resin, supplied from Grizzly Leim GmbH Company for chemicals in Germany. It is based on two components: Component (A) made of native epoxy that is based on linseed oil, and component (B) is the hardener, which is based on a mixture of organic anhydrides (citric acid, oxalic acid,… etc). This bioresin's mixture cure at room temperature (23°C), within ~ 24 to 48 hours. In the data sheet, it is also mentioned that through heat appliance of 100°C high, setting time can be reduced to 5-7 minutes.

a. Selected fossil-based binder – applied for comparison

c.1- Epikote™:

Epikote Resin MGS RIM R035 and Epikure Curing Agent MGS RIM H036 were supplied from Momentive GmbH in Germany. Both components are fossil-oil based. This resin type was chosen due to its low viscosity in comparison to other types released from the same company. Viscosity of the resin is 1300-1600 Mpa.s at 20°C and that of the curing agent is 5-15 Mpa.s at 20°C. The resin and hardener's applied mixing ratios was 100:28 by weight and sets in room temperature within 10-12 hours.

C 3.2. Comparison methodology

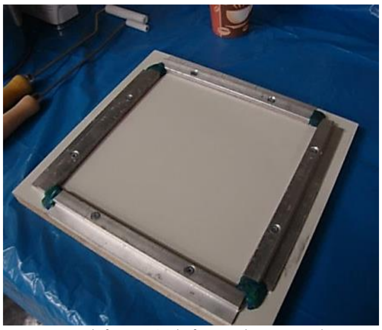
Green rice straw thermoset biocomposites and comparison methodology

TARGET: Green rice straw thermoset biocomposites				Developed biocomposite for comparison	
RS-	**Gripox®**	**RS -**	**PTP®**	**RS**	**Epikote™**
20%wt.	Bioresin that hardens in room temp.	20%wt.	Bioresin that hardens in high temp.	20%wt.	Fossil-based resin that hardens in room temp.

The developed biocomposite RS - fossil-based epoxy resin is prepared and compared with green RS thermoset biocomposites, at the same RS fibre load 20% wt. Technical properties of the developed biocomposites are hereby examined and evaluated, to detect the possible application of the developed green straw- bio-resin biocomposites in external façade applications, depending on the virtual evaluation of the developed samples after free-weathering tests for a time period of 24 months, in accordance to the standard DIN EN ISO 877, (DIN e.V.: Deutsches Institut für Normung e.V., 2011). In addition, RS fibre will be detected if it would change the fire material class of the green RS thermoset biocomposites in collaboration with bioresins, as happened previously in the former developed RS-bioplastics or not. In the last chapter, Chapter E, mechanical properties and weathering resistance differences of the two green biocomposite groups, the thermoplastic and thermoset ones, will be compared at the same RS fibre wt. load (20%) and conclusions for future research work will be accordingly illustrated.

C 3.3. Compounding process and specimens preparation

The two developed green biocomposites: (RS20% wt. - PTP®), (RS 20% wt. - Gripox®) and the reference biocomposite with the same RS load by wt. (RS 20% wt. -Epikote™) were manufactured through the same method. In case of (RS20% wt. - PTP®), the mold was manufactured of metal plates, due to the need of high temperature for polymerization.



1-Metal frame is left partly opened to allow excess resin to flow out

2-Weighing the straw with a high sensitive device with ±0.1 mg tolerance

3-Pouring the mixture in the mold, after applying the suitable molding wax

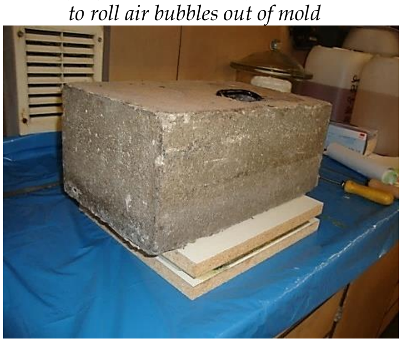
4-Spreading the mixture with a roller

5-Checking the homogenous and full mixture distribution within the mold

6-Applying the transparent foil on the mold to roll air bubbles out of mold

7-Rolling out the trapped air bubbles out of mold and provide flat and shiny surface

8-Covering the mold with the lid



9-Providing excess load on the mold to provide enough pressure

10-Excess resin is released out of the mold with the help of the frame openings

11-Final product

12-Cutting the test samples using a wood saw machine

Table C 3-1. Illustration of the manufacturing process of the developed RS thermoset biocomposites to produce the test specimens.

All samples were first manufactured using a simple flat rectangular mold, surrounded by 2 mm thick frame, where the frames' edges were intentionally left with small openings, to allow excess resin to escape. After mixing the fibre and matrix manually, the mixture was distributed using a roller within the mold, with the applied de-molding wax. The mixture was homogenously laid and equally leveled in the mold, then with the help of a transparent semi-flexible foil, the trapped air bubbles that escaped in the mixture during stirring were rolled out. Afterwards, pressure was applied on the mold's lid, where excess resin was expelled due to pressure applied. Hardening time and temperature differed according to the applied resin. For the first composite (RS-Epikote™), the composite hardened in room temperature within 24 hours; while the second composite (RS-PTP®) hardened at 130°C and took 45 minutes to polymerize. The third developed composite (RS-Gripox®) hardened at room temperature within minimum 24 hours, then after de-molding for another 24-48 hours .

C 3.4. Developed green RS thermoplastic biocomposites - Properties analysis

C 3.4.1. Density

The densities were measured according to DIN 53 479 or DIN EN ISO 1183-1, (DIN e.V.: Deutsches Institut für Normung e.V., 2013), standard of density measurement in the labs of IKT-University of Stuttgart at 23 +/- 1 °C. Applied chopped straw in its raw form is of average 40-100 Kg/m³, after (Jenkins, 1993). Densities of developed materials are displayed as follows:

Biocomposites' Groups	RS20%-Epikote™	RS20%-PTP®	RS20%-Gripox®
Density of composite [Kg/m³]	1049	1077,1	1098
Density of resin (from companies' Datasheets) [Kg/m³]	1090-1160	1070	1100

Table C 3-2. Densities of the developed rice straw thermoset biocomposites

As displayed, there is no big difference between the three developed biocomposites' densities. Comparing the composites' weight to the original resins' weights, it is clear that the advantage of applying the RS-natural fibre, of the low density, 0.02-0.72 (Jenkins, 1993) , as the weight of the composite did not increase, as would have been the case if other synthetic fibres like glass fibres of high density (2500-2700 Kg/m³, (Baunetz Wissen-Glas)) would have been applied. The composites' weights when 20% of RS was incorporated within the resin slightly decreased within classic Epikote™ and PTP® appliance, while almost kept of the same weight when applied with Gripox®.

C 3.4.2. Water Absorption

As illustrated afterwards in Fig. (C 3-2), the green thermoset biocomposites were found more sensitive to water than the RS-classic Epikote™. The highest sensitivity was recorded by (RS20%-Gripox) of around 3,2%, while (RS20%-PTP®) and (RS20%-Epikote™) recorded relatively lower values of approximately 2,2% and 1,9% respectively, after after DIN EN ISO 62- 2008, (DIN Deutsches Institut für Normung e.V. , 2008). As previously illustrated in the last chapter, the average accepted water absorption percentage value in biocomposites can reach uptill 5%, (Gerth, 2013).

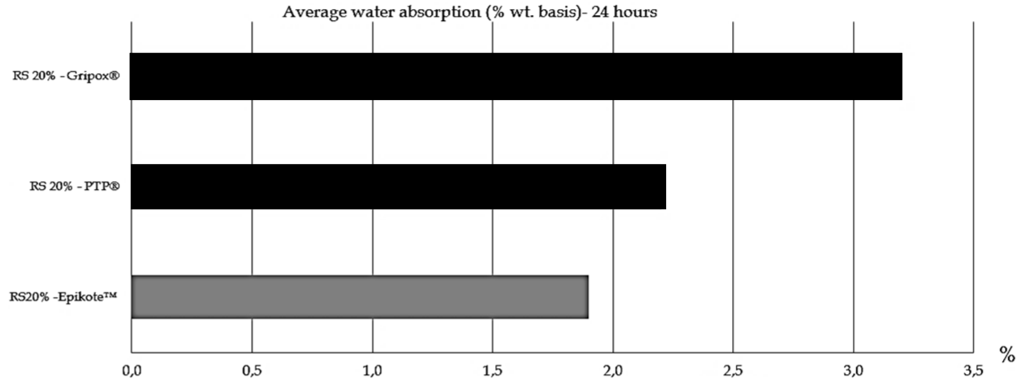


Figure C 3-2. Illustration of the mean value of water absorption of the 3 developed composites at the same fibre load value 20%by mass after DIN EN ISO 62- 2008

C 3.4.3. Mechanical Properties

Tensile strength and tensile stiffness properties

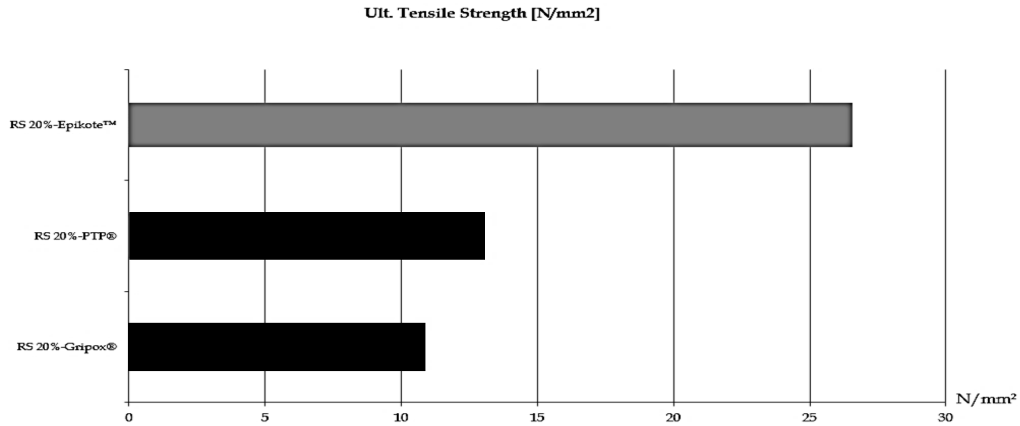


Figure C 3-3. Illustration of the average tensile strength values of the 3 developed RS thermoset biocomposites

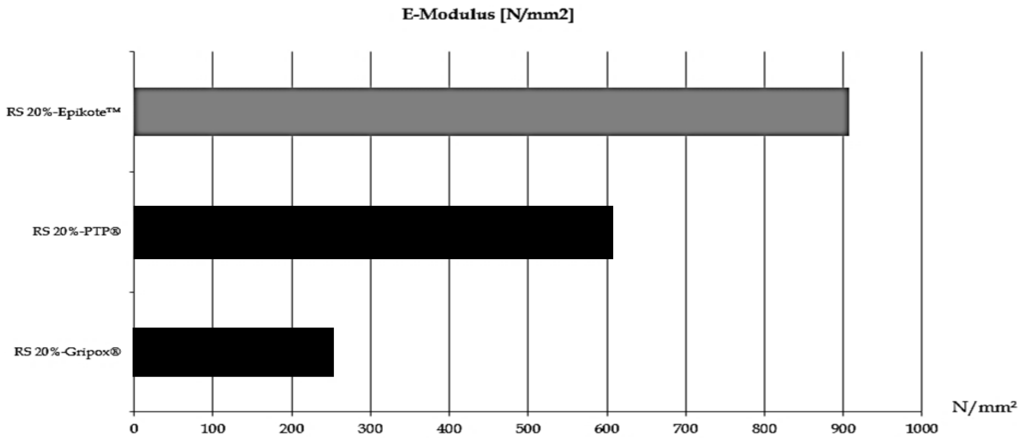
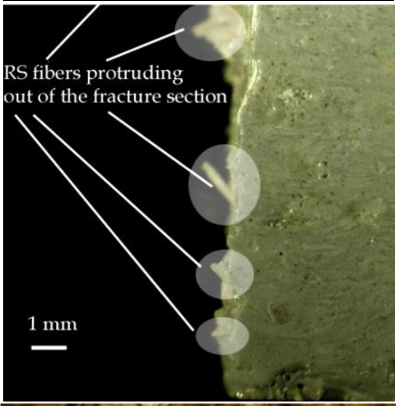
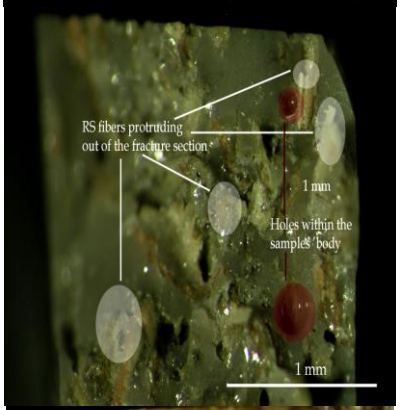
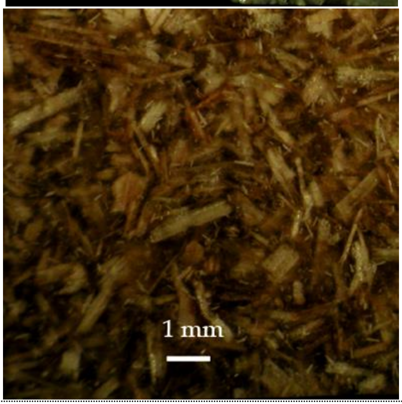


Figure C 3-4. Illustration of the elastic modulus values of the 3 developed RS thermoset biocomposites

Discussion

Through the previous figures, it is clear that the tensile strength properties of the (RS-Epikote™) biocomposite is much higher than (RS-PTP®), then followed by (RS-Gripox®). This same hierarchy in the mechanical properties of the resulted biocomposites remained the same as the same hierarchy of the mechanical properties of the pure resins before applying the fibres, as declared through the technical data sheets of each binder applied. Through comparing the flexural strengths, apparent in their product data sheets of Epikote™ ,Gripox® and PTP®, it was revealed that Epikote™ is 130 N/mm², PTP® is 80-90 N/mm² and Gripox® is 27 N/mm².

C 2.4.4. Morphological Examination

<table>
<tr><th>Sample Name</th><th>Surface</th><th>Section</th></tr>
<tr><td>RS 20%-Epikote ™</td><td>
</td><td>
</td></tr>
<tr><td>RS 20%-PTP®</td><td>
</td><td>
</td></tr>
<tr><td>RS 20%-Gripox®</td><td>
</td><td>
</td></tr>
</table>

Legend: Red: indicates the trapped air in the composite, resulting holes in the structure or surface of probes; White: indicates the protruding rice straw fibres from the body of the specimen through the fracture, indicating successful fibre/matrix bonding

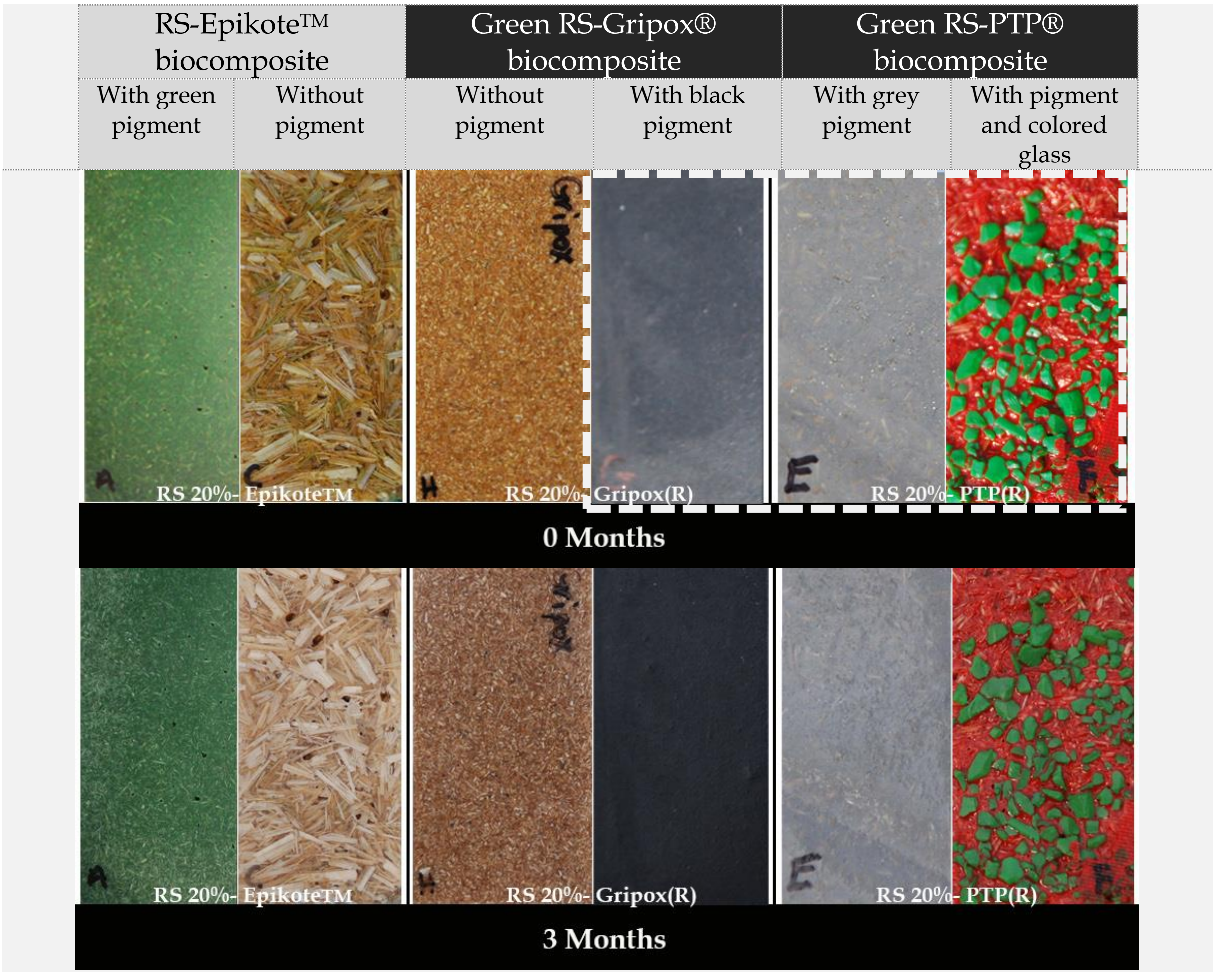
Table C 3-3. Illustration of the microscopic examination of the surface and fracture cross-section resulted from the tensile test of the developed RS thermosets at 20% fibre load by mass.

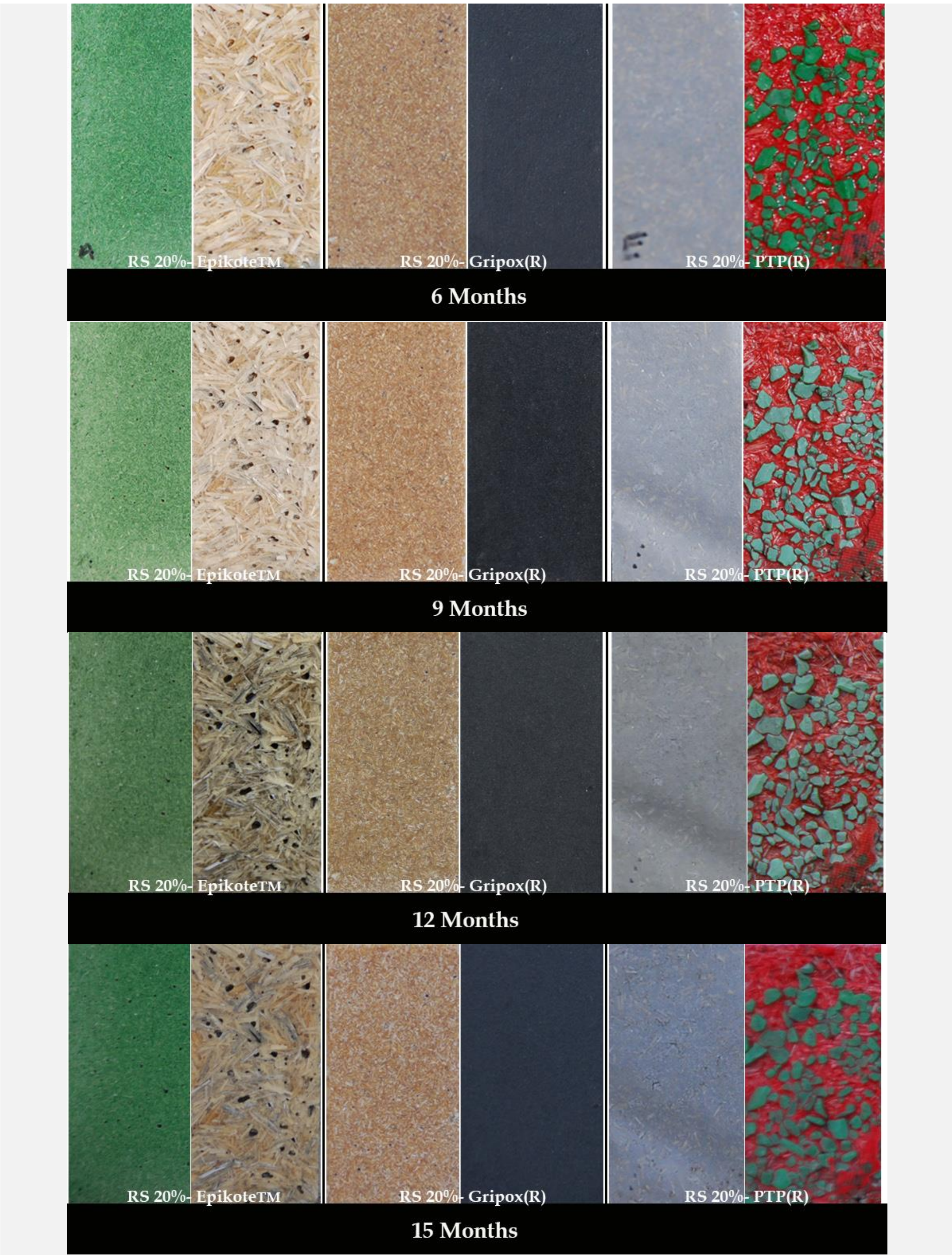
Discussion

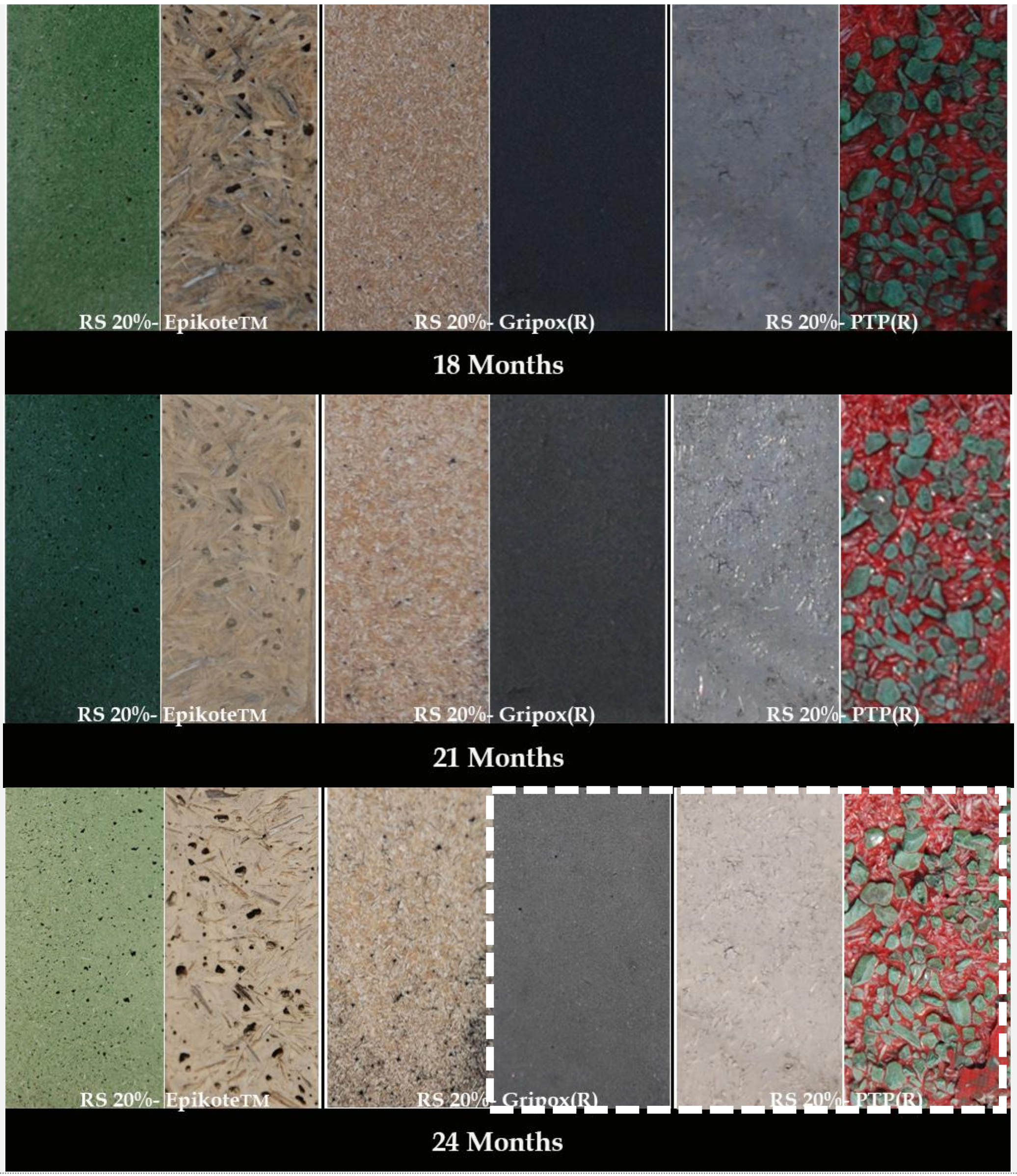
Through the previously illustrated microscopic examination and analysis, it is clear that the applied manufacturing technique was not optimized, as the trapped air bubbles resulted from the stirring process did not fully escape from the composite's structure and was trapped either directly on the specimen's surface or directly underneath it. This reflects that the mechanical and technical properties of the developed thermoset biocomposites should have enjoyed much higher performance if the manufacturing method was optimized. This could be reached through vacuum assistance appliance in addition to the appropriate coupling agent's introduction that should enable the proper fibre/matrix adhesion without air bubbles' encapsulation, which is recommended to be applied in future research work. However, on the other hand, the applied matrices did show compatibility with the applied natural fibre, as the fibres were seen protruding from the fracture section as shown, and not "pulled out" of them. The worst surface within the developed composites can be observed on the (RS-Epikote™) sample, the green one, as air bubbles were much more trapped than the other 2 green biocomposites.

C 3.4.5. Free weathering

The difference within these specimens than former developed thermoplastic ones, that pigments were applied with the different RS-epoxies' biocomposites.




RS 20%- EpikoteTM
RS 20%- Gripox(R)
RS 20%- PTP(R)
6 Months
RS 20%- EpikoteTM
RS 20%- Gripox(R)
RS 20%- PTP(R)
9 Months
RS 20%- EpikoteTM
RS 20%- Gripox(R)
RS 20%- PTP(R)
12 Months
RS 20%- EpikoteTM
RS 20%- Gripox(R)
RS 20%- PTP(R)
15 Months



Note: Apparent colours are original un-modified ones and accordingly extra darkness or lightness due to natural lighting' differences after seasons' changes, can be noticed.

Table C 3-4. Visual comparison between the natural free weathering effect after DIN EN ISO 877.

Test evaluation and discussion

Through the previous illustrated visual comparisons, it is clear that both the RS-bio-based epoxy composites have shown equal or better weathering resistance to the RS-fossil-based matrix composites. Better weathering resistance appears through the visual surface comparisons and observational inspections through both (RS-PTP®) samples. It is clear that the pigmented products have shown much resistance to surface-changing than those of uncolored samples, as in the case of both (RS-Epikote™) and (RS-Gripox®) compounds. Black pigmented (RS-Gripox®) and grey as well as red pigmented (RS-PTP®) have shown the best performance and un-change in surface features, when visually compared.In case of un-pigmented (RS-Epikote™), large dark spots are clearly seen on the sample's surface, due to the trapped air bubbles that escaped in the mixture during manufacturing and were not successfully removed, causing rot to penetrate within the surface and cause this bad visual effect. This same effect appeared on the un-pigmented (RS-Gripox®) specimen, in the last photo, after 24 months, especially at the corners. This is due to the presence of the same air-bubbles' issue, but concentrated on the cut-side of one of the corners of the sample, that allowed the microbial attack to spread through it. Generally, when the RS thermosets' biocomposites' manufacturing techniques would be optimized through the vacuum-assistance applying, better surface quality would be expected. It was also remarked that pigments' appliance improved the surface quality, not only from an aesthetic perspective, but also in respect to the weathering and UV-resistance.

C 2.4.6. Flammability Behavior

Biocomposites' Groups (at 20% RS wt.)	RS20%-Epikote™			RS 20%- PTP®			RS 20%-Gripox®		
[sec.]	$t_{b\,1}$	$t_{b\,2}$	t_{b3}	$t_{b\,1}$	$t_{b\,2}$	t_{b3}	$t_{b\,1}$	$t_{b\,2}$	t_{b3}
Spec.1	127	0	0	80	0	0	135	0	0
Spec.2	118	0	0	117	0	0	126	0	0
Spec.3	157	0	0	106	0	0	137	0	0
Spec.4	140	0	0	92	0	0	122	0	0
Spec.5	116	0	0	103	0	0	130	0	0
Cotton Indicator Ignition (Yes/No)	**No**			**Yes**			**No**		
Complete consumption of specimen (Yes/No)	**Yes**			**Yes**			**Yes**		
Notes and Conclusions	**The samples were turned to coal. The fire reached the clamp, but after burning the fibres enabled the samples' figure to stay stable and keep-on hanging, without releasing any burning droplets on the cotton indicator. The burning time was much longer than what the standard permits, hence was beyond material ranking. However, the burning attitude shows that the material could reach much better classification if RS mass% was increased.**			**The burning attitude was much worse than the previous samples, as the samples burnt in shorter time, but completely dropped on the cotton indicator. It cannot be guaranteed to have better burning resistance in case of only increasing the RS fibre content, without adding fire-retardants' additives.**			**The samples were coaled as in the first case and the form kept stable and hanging from the test clamp. This indicates here as well the possible increase in fire-resistance capability, based on the natural RS fibre load. The material did not reach accordingly to a specific material class, according to the standard applied.**		

Table C 3-5. Illustration of the flammability attitude of the RS 20%- filling load with the chosen epoxies, of different basis: fossil-based: Epikote™andplant oil-based: PTP® and Gripox® after UL1694.

Test evaluation and discussion

The developed materials were all beyond the standard, and could not be classified within the fire-classes according to the applied standard: UL 1694.

Generally, it was remarked that the (RS-Epikote™) and (RS-Gripox®) flammability-bahvior were much better than that of (RS-PTP®). The first two mentioned materials were completely burnt, but did not have any droplets on the cotton indicator and did not cause its ignition, in contrary to what was remarked from the last mentioned material, (RS-PTP®), which was completely burnt and dropped on the cotton indicator, burning it completely. (RS-Epikote™)

and (RS-Gripox®) were both coaled, and fire reached the test clamp, but it was remarked that when the fire started moving up across the sample's body, the previous sample's parts rapidly coaled and fire vanished alone, leaving the sample's body in a stable form, still hanging to the test clamp.

This indicates the possible effect of the RS as an alternative natural flame-retardant with much higher fibre load in the case of (RS-Epikote™) and (RS-Gripox®), as in the case of (RS-elastic binder), that was mentioned in the first part of this current chapter. In case of (RS-Gripox®), this expectation cannot be hypothesized, due to the high flammability behavior illustrated, with the 20% applied fibre ratio.

However, it is worthy in future work to apply higher fibre ratios with the applied matrices and apply the same fire test to evaluate if this would change the material's class. This should in this case be applied with optimized production techniques in assistance of vacuum- supply.

C 2.4.7. Environmental assessment with respect to recyclability and biodegradability

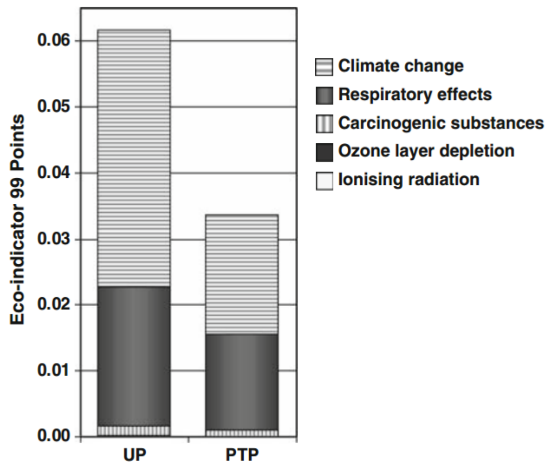
LCA (Life Cycle Assessment) for a thermoset biocomposites based on (Hemp-PTP®) biocomposites was applied (Schmehl, et al., 2007). They compared this green composite, which was applied as a bus body component, with another composite based on glass fibre and polyester resin (GF-UP) applied for the same application.

The comparison was applied through entering a number of factors within the assessment methodology applied using Eco-indicator 99, including the damage categories of human health, ecosystem equality and resources. The outcome was found that green composite showed much better results within the environmental impacts, especially within the damage categories of fossil fuels/energy resources and climatic change, Fig. (C 3-5).

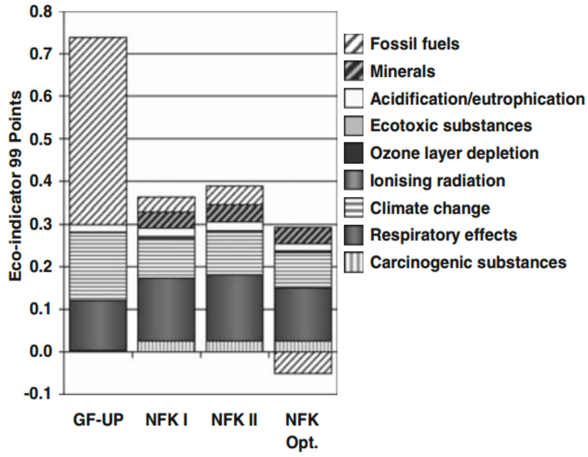
Similarly, within this research, it could be deduced through the (RS- PTP®), that the outcome product which should be applicable in the building sector should enjoy much better environmental impacts than the classic composites applied within the same applications.

According to (Müssig, et al., 2006), the previously mentioned developed exterior bus component made from hemp fibres combined with the vegetable-oil based resin PTP® using the sheet-molding-compound technology (SMC), did not enjoy any extra technical advantages over the components developed from conventional components based on petrochemical resources, according to the end-of –life vehicles' regulations.

However, according to the authors, it was emphasized that the application of renewable resources has advantages in terms of recycling technologies, which will become economically more important in the future.



Environmental impact assessment of the classic polyester resin (UP) and the bio-resin applied (PTP®), putting the whole life cycle into consideration, from resources applied till the end of life options



Environmental impact assessment of the glass fibre-polyester composite (GF-UP) and (NFK I, NFK II and NFK Opt.), which are three different green natural fibre biocomposite variations, using PTP®, and all applied for the same application in the automotive body

Figure C 3-5. Illustration of the environmental assessment of the natural fibre PTP® composite in comparison to the classic GF-polyester composite. The value of environmental impact of the resins is firstly indicated, then after the natural fibre's incorporation, forming the composite, after (Schmehl, et al., 2007).

Optimum environmental benefit would be applicable, if the material production took place in the same plot/country, in which all composite's components are industrialized, to save transport costs, which plays another important environmental impact factor. In Europe, where this resin manufacturing company exists, namely in Germany, available wheat straw is then recommended to be applied instead of rice straw.

On the other hand, worldwide, where soybean or linseed or other plant-based oils abundantly exist, which are not usable in feedstock supply, bio-based epoxies' industry could largely expand and straw types, depending on the available type in the country, could be applied to replace this bio-epoxy in the highest possible ratio, especially for exterior architectural applications, to achieve complex geometries that could not be easily produced using natural fibre-thermoplastics. This combination would be expected to reach high beneficial environmental value as well as economic one.

Generally, thermoset composites could be thermally recycled through pyrolysis to gain the saved inner energy back. In addition, crushing the whole composite after the end of its useful life-time, and applying it as filler in other composites is another method of recycling the NF-thermoset composites.

Thermoset composites are known to be not compostable, due to the rigid double bonding formation within the thermoset composite's structure, whether this composite is of purely bio-basis or not, unlike the biodegradable bioplastics, that were thoroughly discussed in the last chapter.

C 3.5. Conclusions

Developed biocomposites	RS 20%-Epikote™	RS 20%-PTP®	RS 20% -Gripox®
Fibre Price	- -	- -	- -
Polymer Price	0.8-1.8 x	x	3 x
Mechanical properties	+ +	+ -	+ -
Water Absorption	+	+	+
Compatibility/Morphology	+ -	+	+
Fire Resistance	-	- -	-
Natural weathering	+ -	+ +	+ +
Biodegradability	- -	- -	- -

Legend: - : low/ bad/ un-reasonable , + : high/good/reasonable

Prices comparison are symbolized after regarding contemporary prices of Epikote™ (Lange und Ritter GmBH) and (Momentive Specialty Chemicals Stuttgart GmbH, 2014), PTP® (Klaus Dippon- B.A.M. GmbH, 2014)and Gripox® (Grizzly Leim GmBH)

Table C 3-6.Comparison between the technical properties and prices of the developed biocomposites

It is clear that (RS-PTP®) composites have a high economic value that would enable it to have an expected positive influence if supplied in the contemporary market. However, extra amounts of RS should be compounded in the end-product and flame resistance behavior should be further optimized. As displayed, (RS 20%-Epikote™) reference material has shown the highest mechanical performance in comparison to the other two developed green biocomposites. (RS 20%-Gripox®) has shown the lowest tensile properties performance among the developed biocomposites, while densities were almost the same due to the relatively equal high density binders.

Water absorption was recorded for all composites below 3.5%, which is an appropriate value, since no coating has been applied on the developed materials' surfaces. Morphological microscopic examination has shown similar compatibility between the different matrices and the natural fibre. Through the examination, inspite of the escaped air bubbles within the samples' structure, still protruded fibres existed within the specimens' fractures, reflecting compatibility.

Flammability behavior was the worst within the (RS 20%-PTP®). All developed materials did not succeed to reach a specific fire material class according to the standards applied, without the application of flame-retardant additives. On the other hand, (RS 20%-Epikote™) and (RS 20% -Gripox®) enjoyed better flammability performances, as the materials coaled under the applied conditions, but did not have any droplets on the indicator.

The best technical property of the developed green biocomposites was within the natural weathering performance, especially within the pigmented specimens. Inspite that the samples were not modified with UV-resistance additives or laminated with extra coatings, green biocomposites' specimens preserved their external textures and features without decay or color loss, especially the developed material (RS20%-PTP®). Accordingly, the green (RS-thermoset biocomposites) would be applied to suit external applications as non-structural façade screens, after further developments concerning fire-retardation. However, it is vital within future research work, to re-evaluate the specimens' mechanical properties after weathering.

Discussion:

Open debate regarding the applied bioresins in the developed green thermoset biocomposites:

One of the critical evaluations of the natural fibres-bio-resins' combinations, is the high-temperature curing's need, as in the case of (RS-PTP®) condition, which is one of the drawbacks of the bio-derived resins of high renewable resources' contents. In such cases, high temperature is applied to force the accelerator to activate in relatively short time, which is another important economical aspect within the mass-production within industrial plants. On the other hand, the other straw-bio-derived resin's combination in which no heat is needed to be applied, as in the case of (RS- Gripox®), is environmentally-friendly from one point of view, but on the other hand, it would not be practical enough in the pilot-scale applications. In this case, the industrial investor would not prefer this type, from a commercial point of view, since the longer the manufacturing time, the more expensive the end-product is expected to be. However, future research work for chemical developments within such types of room-temperature setting bio-resins should further take place, to accelerate the setting time so as to meet the industrial and market needs accordingly.

D.

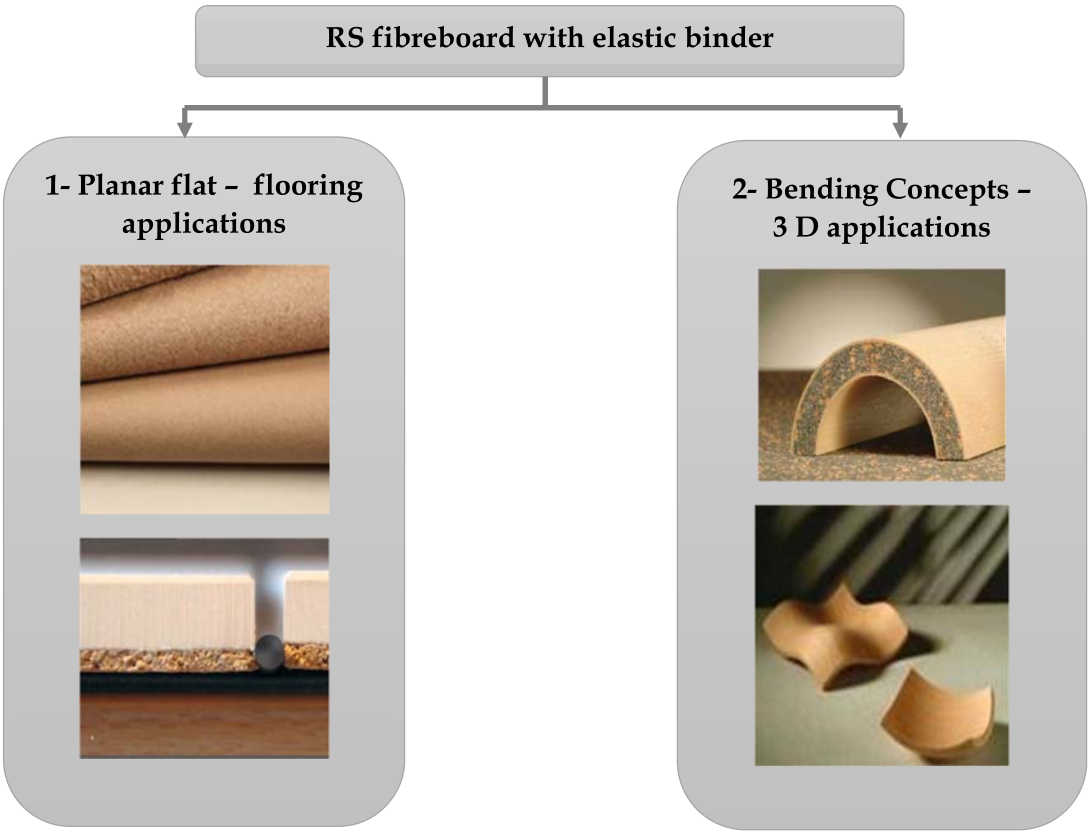
Architectural Applications

D. Architectural Applications

D 1. Applications of Rice Straw fibreboard with elastic binder

According to the developed materials' analysis in the previous chapter, the possible applications of the RS fibreboard with elastic binder at 80% fibre wt. can be proposed indoors either in planar or free-form geometries. The planar applications are expressed either without veneering in the form of flooring systems, including anti-slip mats, sports' mats and flooring systems as well as other combined flooring systems, or with veneering in the form of free-form interior partitions', fittings' and furniture's cores making use of the elastic nature of the developed fibreboard.

Applications possibilities are graphically expressed as follows:



D 1.2. Planar interior applications

D 1.2.1. Direct flat applications: Flooring applications

Generally and as previously declared, the developed elastic fibreboards should provide a non-slippery effective behavior due to both the abrasive silica contents and as a natural characteristic of the elastomer applied. Accordingly anti-slip mats and shocks absorbers are the direct possible applications of the flat elastic fibreboard realized. In addition, the high density of the realized composite is one of the main demands of flooring applications, that should be of minimum 950 Kg/m^3 to create a hard, non-scuff flooring surface, (Wasylciw & TAPPI, 1998) .

D 1.2.2. Anti- Slip mats

Flooring mats, Fig. (D 1-1), in the form of rolls can be applied for anti-slip functions, in dry areas. Small gaps at the bottom of the floor mat can add to the anti-slip effect, Fig. (D 1-2). These gaps create air-friction between the mat and the underlying-surface, which prevents the mats from moving. The applications for such mats include interior children playgrounds, Fig. (D 1-3), as well as sports-, Fig. (D 1-4) and Yoga-mats. The mats could also be applied in the form of interlocks and can be pigmented within the mixing processes, the same way as within the classic plastic industry.

Figure D 1-1 .Wood and cork elastic fibreboards (Wacker Chemie AG, 2012)

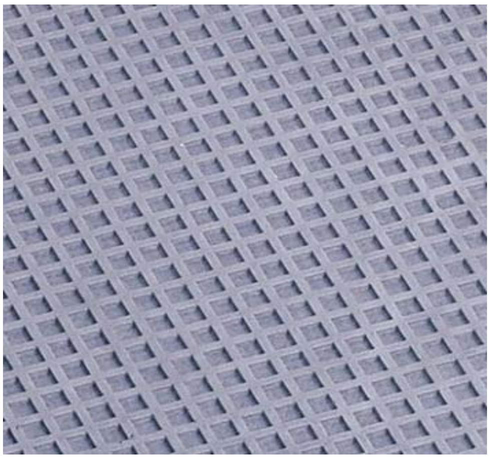


Figure D 1-2. Small gaps at the bottom of anti-slip mats for extra anti-slipping effect's adjustment, (BSW Berleburger Schaumstoffwerk GmbH, kein Datum)

Figure D 1-3. Pigmented fibreboards -interior children playing spaces. Photo credit: (Interior Gallery Design, kein Datum)

Figure D 1-4. Flooring mats for cushioning applications under heavy sport objects. Photo credit: (BSW Berleburger Schaumstoffwerk GmbH, kein Datum)

D 1.2.3. Different flooring combination systems, serving as a substrate

- The RS elastic fibreboard can be applied as one or more layers in the form of multi-layered flooring system, to make good use of the anti-slippery effect that can be applied, instead of sticking the regular flooring tiles permanently to the sub-floors. This would allow dry fixation method of ceramic or marble floor tiles, which offers many ecologic and economic advantages, including adhesives 'cost and adhesion time's savings. In addition, the tiles can be replaced at any time, without extra wastes' release, Fig. (D 1-5).

- Another possibility would be through combining the elastic fibreboard as multiple layers underneath flexible thin flooring layers, like leather and textile flooring systems; Fig. (D 1-6).

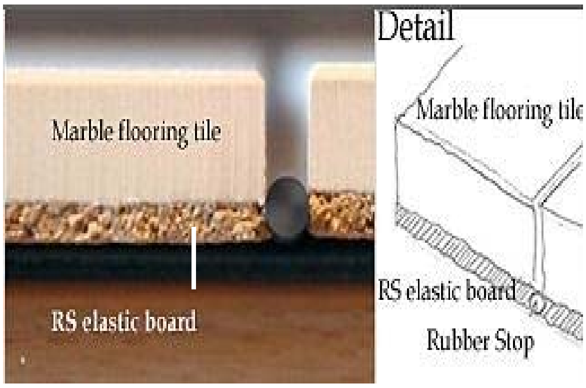


Figure D 1-5. Flooring system combination applying the elastic fibreboard instead of sticking the marble permanently on the base flooring. (Combined Marble flooring system photo: (Wacker Chemie AG, 2012). Detail sketch: Dahy, H.

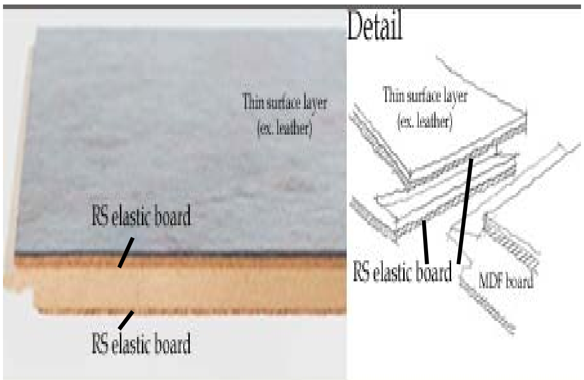


Figure D 1-6. Combined leather flooring system, applying the developed fibreboards for extra rigidity, non-slippery and extra walking comfort effect, board photo credit: (Wacker Chemie AG, 2012). Detail sketch: Dahy, H.

D 1.3. 3D and free-form interior applications

D 1.3.1. Bending and fixing the elastic fibreboard through veneering

The elastic nature of the developed fibreboard provides the possibility of creating free-form geometrical applications. These can be produced through bending the board, according to the form needed to be produced, Fig. (D 1-7), then fixing this form through veneering as illustrated in Fig. (D 1-8). The applications include 3D-objects, furniture and interior fittings.

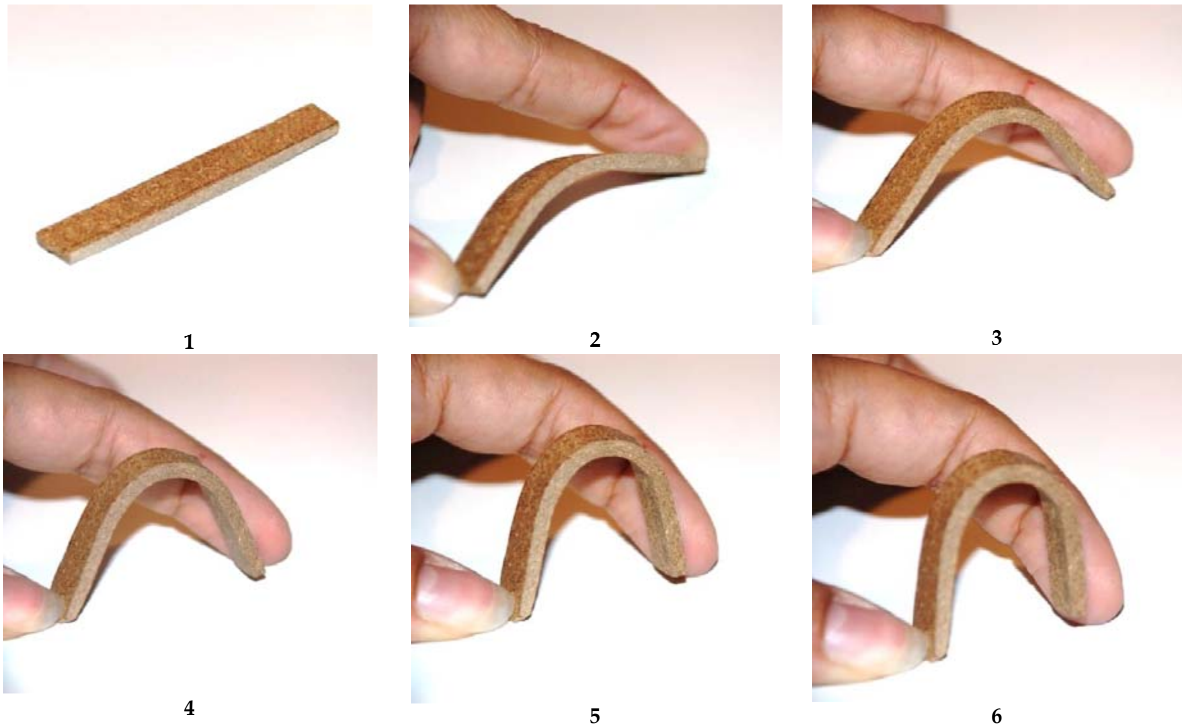


Figure D 1-7. Illustration of the bending concept and forming possibilities of the developed elastic RS fibreboard, before fixing the form with extra veneer layers, as a method for gaining free-form surfaces and bodies.

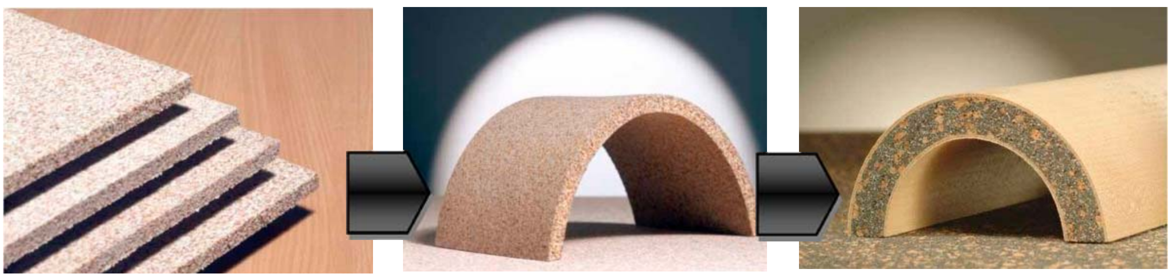


Figure D 1-8. Illustration of turning the elastic fibreboard Recoflex® from BSW Firma from a flat board to a 3D formed one through bending, then fixing the form through veneering, photo credit: (BSW BerleburgerSchaumstoffwerk GmbH, 2013).

D 1.3.2. 3D interior fittings and exhibition construction

Within Fig.(D 1-9), a conceptual interior façade application, here named as 'Bubble-Façade' is here designed and based on a bent plate that is fixed in a cylindrical form and fixed using hooks on the interior façade's surface, forming the desired free-design. Through the same concept of bending and veneering the bent form for fixation, many free-form geometrical applications can be reached including interior fittings and curved partitions, Figs. (D 1-10), (D 1-11).

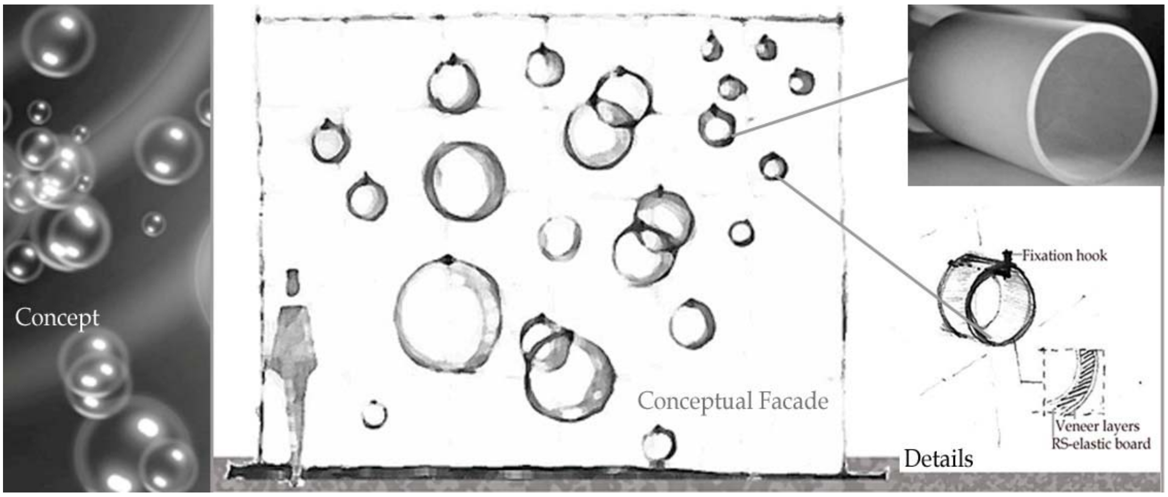


Figure D 1-9. Illustration of an interior façade design conception, depending on the flexibility of the RS elastic fibreboard developed, "Bubble-Façade"

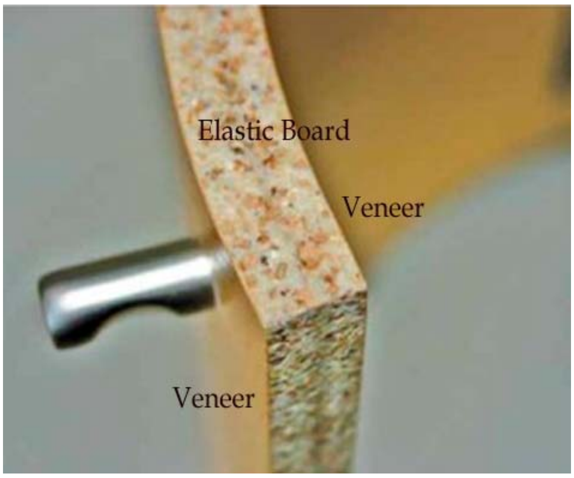


Figure D 1-10. Detail of a free-form interior fitting formed through veneering the elastic fibreboard, (BSW BerleburgerSchaumstoffwerk GmbH, 2013).

Figure D 1-11. Free-standing free-form acoustic panels, from veneered elastic fibreboards, (BSW BerleburgerSchaumstoffwerk GmbH, 2013)

D 1.3.3. Free-form objects and furniture

Sophisticated free-form objects can be also created through twisting and free-forming the developed elastic form as indicated in Fig. (D 1-12), followed by veneering the resulted form to fix it, forming a free-form sandwich panel, where the elastic fibreboard form the core of the form.

The outcome can be applied in different interesting applications including free-form furniture, Fig. (D 1-13) and interior fittings.

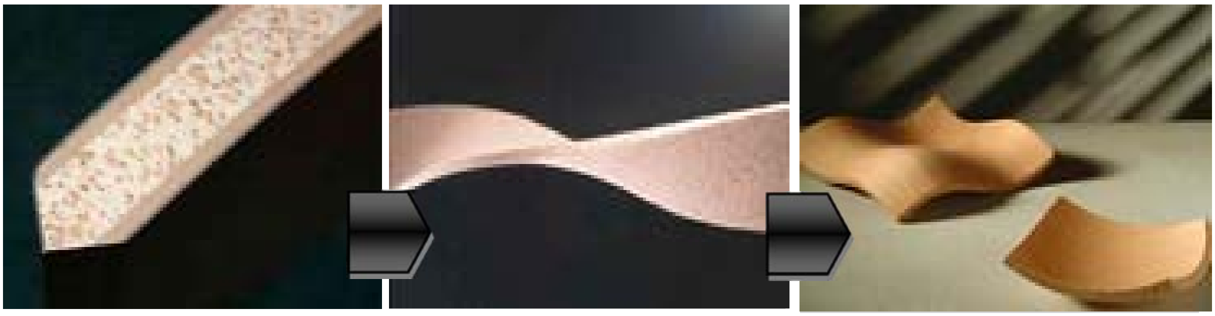
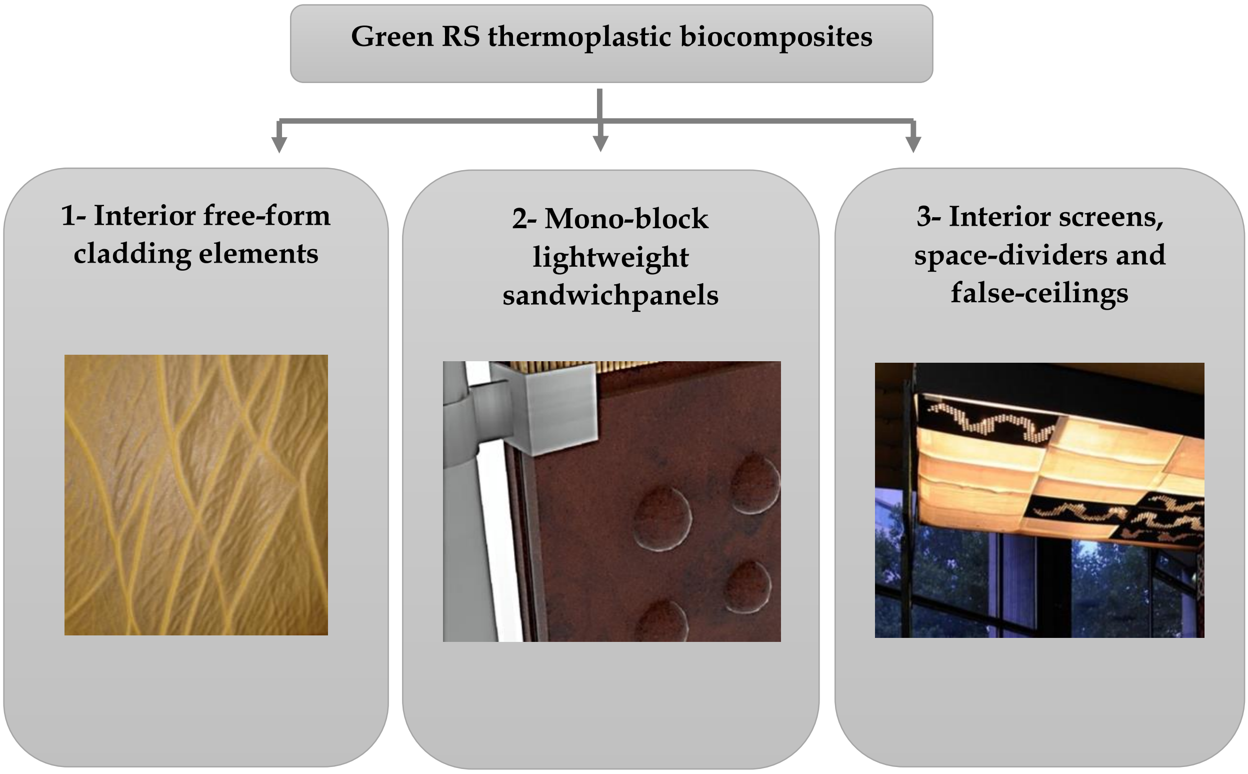


Figure D 1-12. Illustration of the twisting possibilities and the gain of complex geometries through the flat elastic fibreboard. Photo credit: (BSW BerleburgerSchaumstoffwerk GmbH, 2013).

Figure D 1-13. Examples of free-form furniture designs depending on the elastic fibreboard applied as the core and fixed by veneer forming free-form sandwich panels. Photo credit: (BSW BerleburgerSchaumstoffwerk GmbH, 2013).

D 2. Applications of green Rice Straw thermoplastic biocomposites

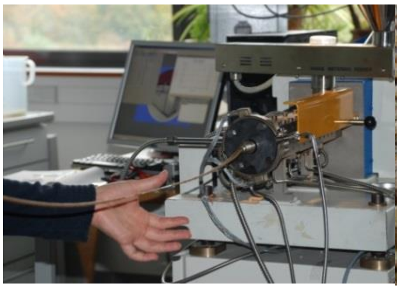
According to the conclusions presented in the last chapter, the possible applications of the developed green RS thermoplastic biocomposites can be presented as follows for interior applications:



D 2.1. Interior free-form cladding elements

These applications depend mainly on thermoforming processing, in which a mold that should be previously designed would be applied within the vacuum thermoforming machine.

Within the following, visualization of the needed production stages of the developed green RS- bioplastics plates, to be afterwards thermoformed and applied as a free-form cladding system is illustrated as follows:



1- Compounding the straw and bioplastic within the twin screw extruder

2-The straw thermoplastic granulates after extrusion

3-RS-bioplastic plates after pressing or plate-extrusion processing

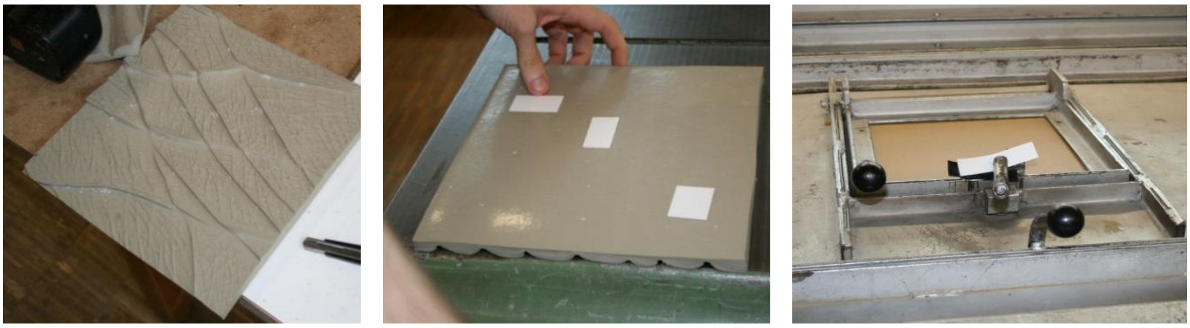
4-The mold is adjusted within the thermoforming machine

5-The thermoformed lignin-cellulose sheet simulating the straw bioplastic proposed thermoformed sheets

6-The final proposed product fixed as an interior cladding element

Figure D 2-1. Illustration of the production procedures of the proposed developed green RS thermoplastic panels, simulating its thermoforming and application

The applied sheet was a 2 mm lignin-cellulose extruded panel. The molds applied were made from rubber and supplied from Reckli GmbH, which usually supplies those rubber mattresses for concrete molding. The detailed production process is illustrated within the following figure, Fig. (D 2-2). During thermoforming, the thick plate of 5 mm did not function, while the thinner plate of 2 mm functioned properly as illustrated.



1-Reckli® rubber mold after being drilled in the deep contour lines

2-Fixing thin plates at the back of the mold for stabilization

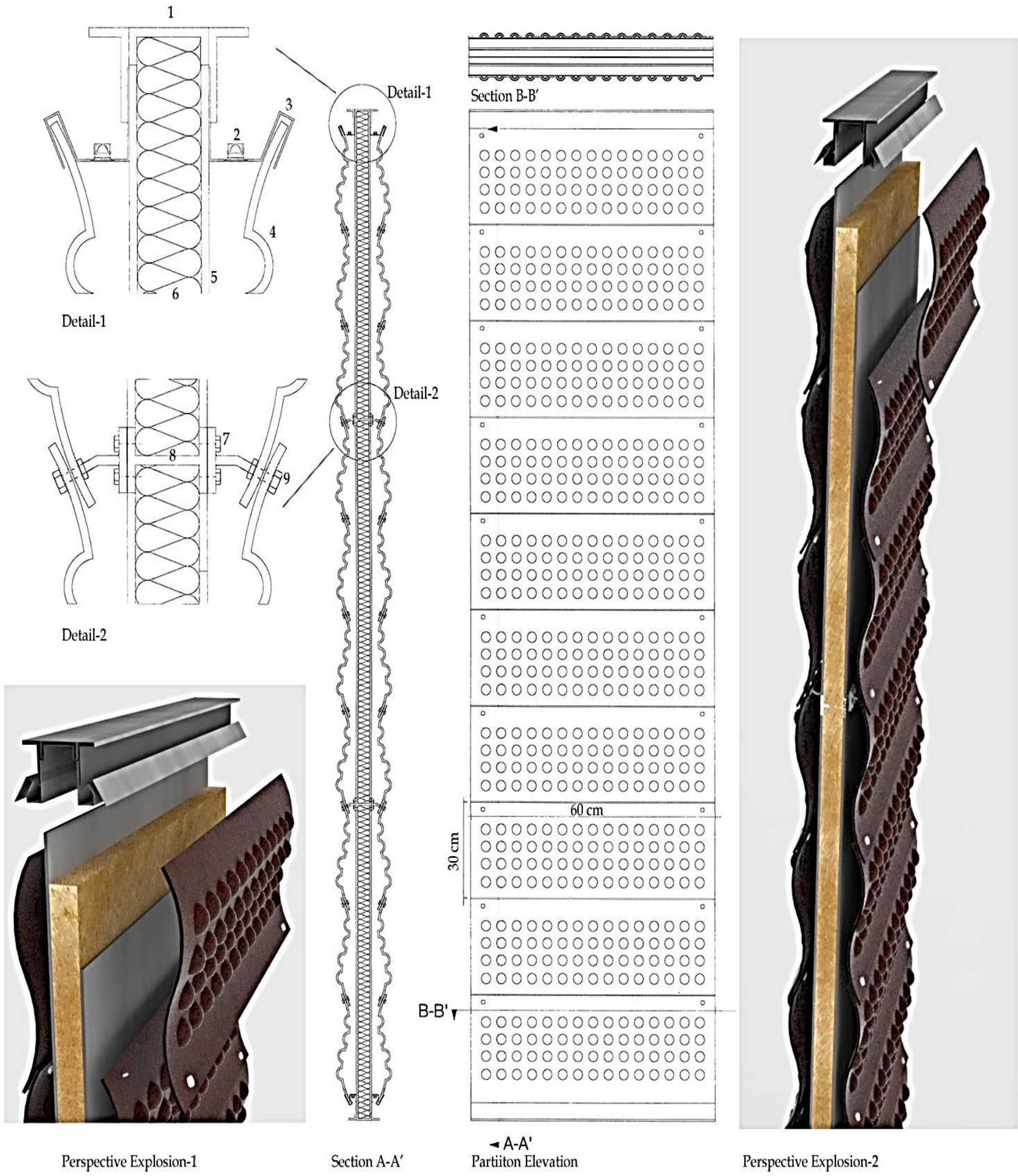
3-The mold is applied underneath the heating plates, and the cellulose-lignin panel is fixed above

4-The cellulose-lignin panel after being thermoformed

5-The final products before and after fixation as an interior cladding element

Figure D 2-2. Illustration of the thermoforming process of the free-form green thermoplastic panels.

The thermoformed panels can be either fixed for cladding purposes, or applied as a main part of a combined partition for interiors, in combination with insulation boards, as presented in Fig. (D 2-3)

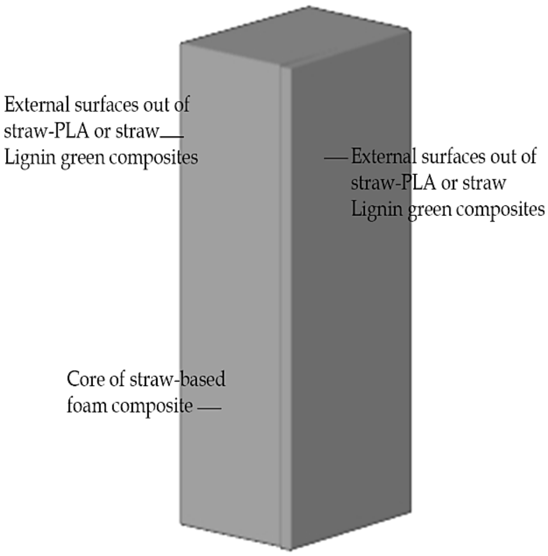


1-Upper integrated double T-aluminum profile; 2-Lighting unit, integrated at the top and bottom of the partition; 3- Aluminum sheet profile closing the upper and lower panels to the hidden backward construction; 4- The upper thermoformed RS-lignin panel; 5- Elevation of the aluminum profiles holding the skeleton of the background partition construction; 6- Cellulose thermal insulation boards; 7- Plates and bolts holding the background construction with the tilted profile holding the inclined free-form thermoformed plates; 8- I-shaped aluminum profiles between cellulose insulation boards; 9- exterior bolts holding each two thermoformed plates.

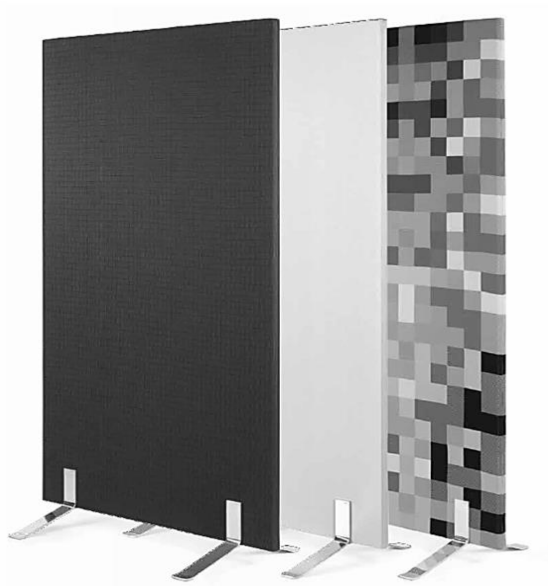
Figure D 2-3. Visualization of the concept of integrating thermoformed RS-lignin panels, in a classic interior partitions construction system

D 2.2. Mono-block lightweight sandwich panels

Another form of applying the developed green RS agroplastics is applying them as covering layers of mono-block sandwich panels, in the form of lightweight free-standing partitions with acoustic integrated functions, which are applicable in office buildings, houses, exhibitions and shops. The two external sandwich panel layers should be manufactured in a separate process of the proposed green biocomposites and could be left in their planar extruded form, as in Fig. (D 2-4) or could be thermoformed as previously described, and combined in the same method with the core, as in Fig. (D 2-5). The inner foam core, which is here suggested could be composed of straw-based biofoam biocomposite that would be either injected between the two external layers of the monoblock, or glued from both sides with a bio-based adhesive system, to be covered with the pre-thermoformed panel's external layers.



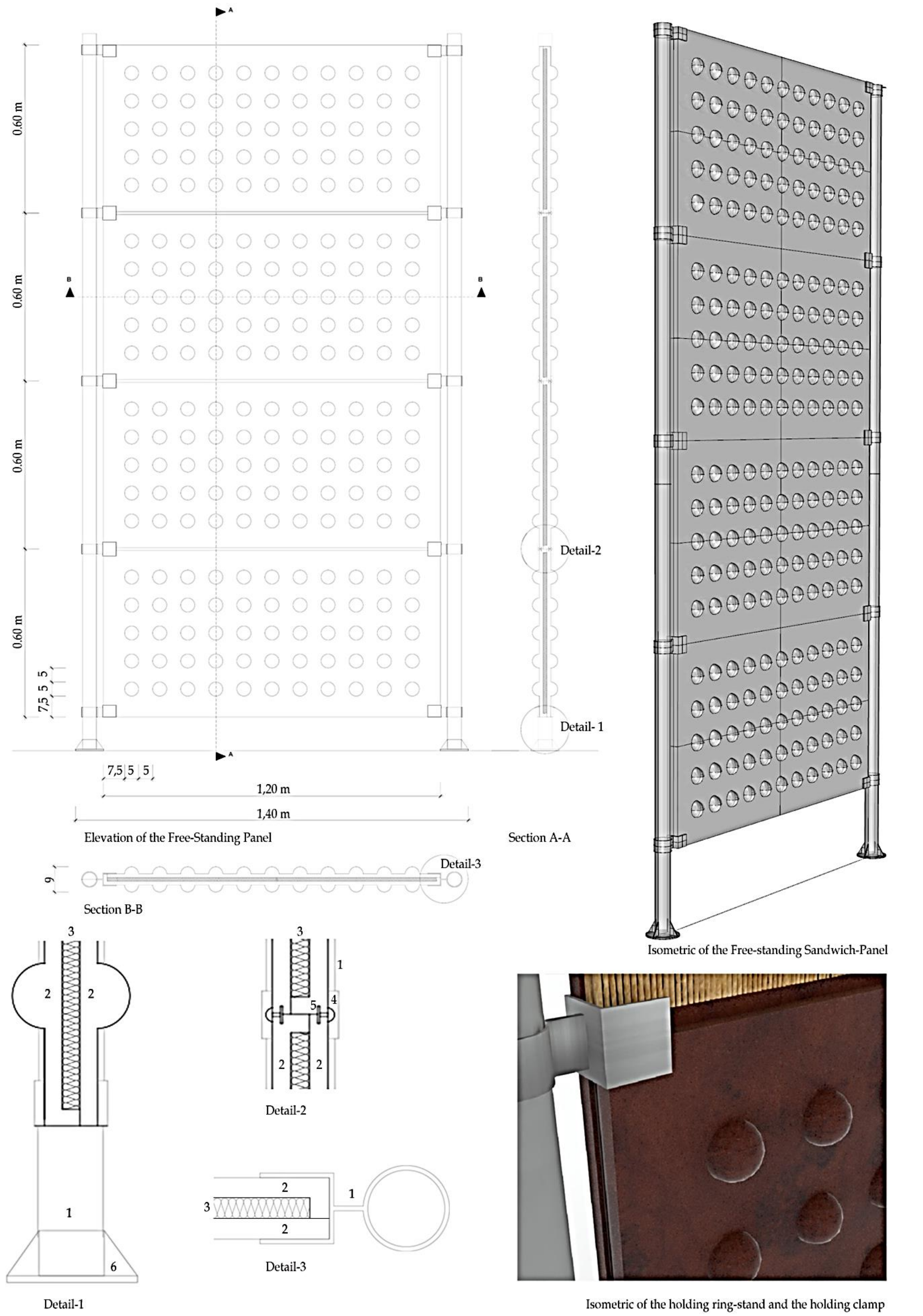
Sketch illustrating the concept of the monoblock lightweight sandwich panels from the developed and suggested straw-based green composites



Free-standing acoustic partitions from lightweight materials. Photo credit: rossoacoustic®-nimbusgroup

Figure D 2-4. Illustration of the monoblock lightweight sandwich panel interior concepts that can be manufactured from straw-based composites

Monoblock lightweight sandwich panel with thermoformed surfaces is visualized through the following detailed design:



1-Ring-stand combined to a holding clamp; 2- Thermoformed RS-lignin skin panels of the sandwich panel; 3- Biofoam composed of straw-biofoam ; 4-Elevation of the holding clamp; 5-Pigeon-tail detail combining upper and lower panel skins; 6- The standing ring flanges

Figure D 2-5. Illustration of a free-standing mono-block panel concept with thermoformed RS-bioplastic skin and a straw-biofoam core

D 2.3. Interior screens, space-dividers and false-ceilings

D 2.3.1. False ceiling[1]

This false-ceiling prototype panels is one of the possible applications of the pigmented RS-PLA biocomposites in the form of panels that can range from 2-3 mm. The panels could be laser-cut according to a pre-defined design as in this example. The laser-cut pigmented RS-PLA could be combined with translucent RS-PLA panels with low fibre-loads to reach this translucency's effect. In this example however, full translucency was achieved from pure plastic sheets, without RS fibres' appliance.

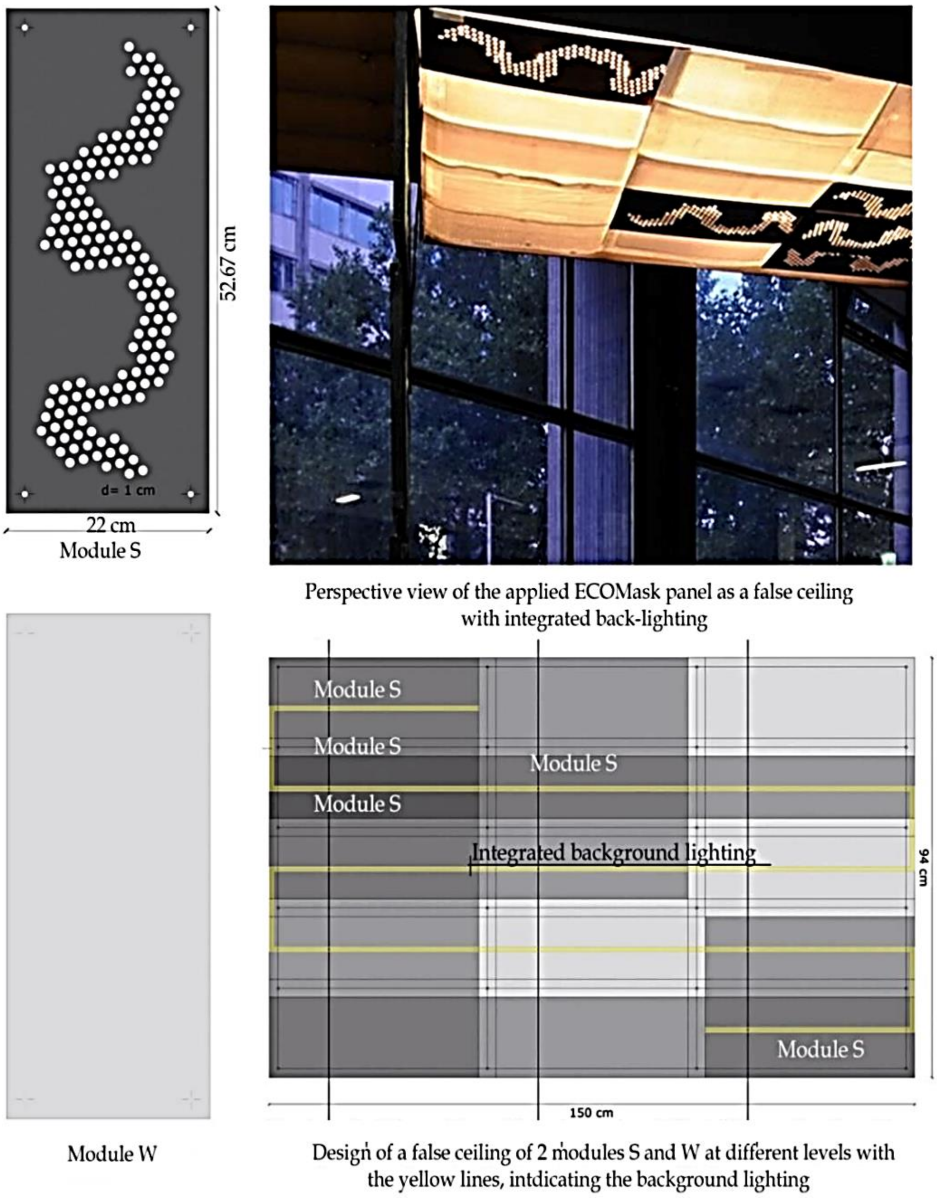


Figure D 2-6. False-ceiling panels with integrated back-lighting.
Photo credit: Up-right: Miklautsch, B.; Others: Students Group

[1] This panel's manufacturing was within an educational course supervised by the author. Students participated were: Cinzia Gallina, Mario Pessa

D 2.3.2. Interior screens and space dividers[2]

Interior screens and space dividers can be applied in the form of laser-cut flat panels. Thermoformed bio-plastic panels can be integrated to be applied within the laser-cut holes, or the panel can be applied as it is directly after cutting, without extra layers, as shown in the interior design. The flat cut screens are agro-fibre reinforced PLA plates.

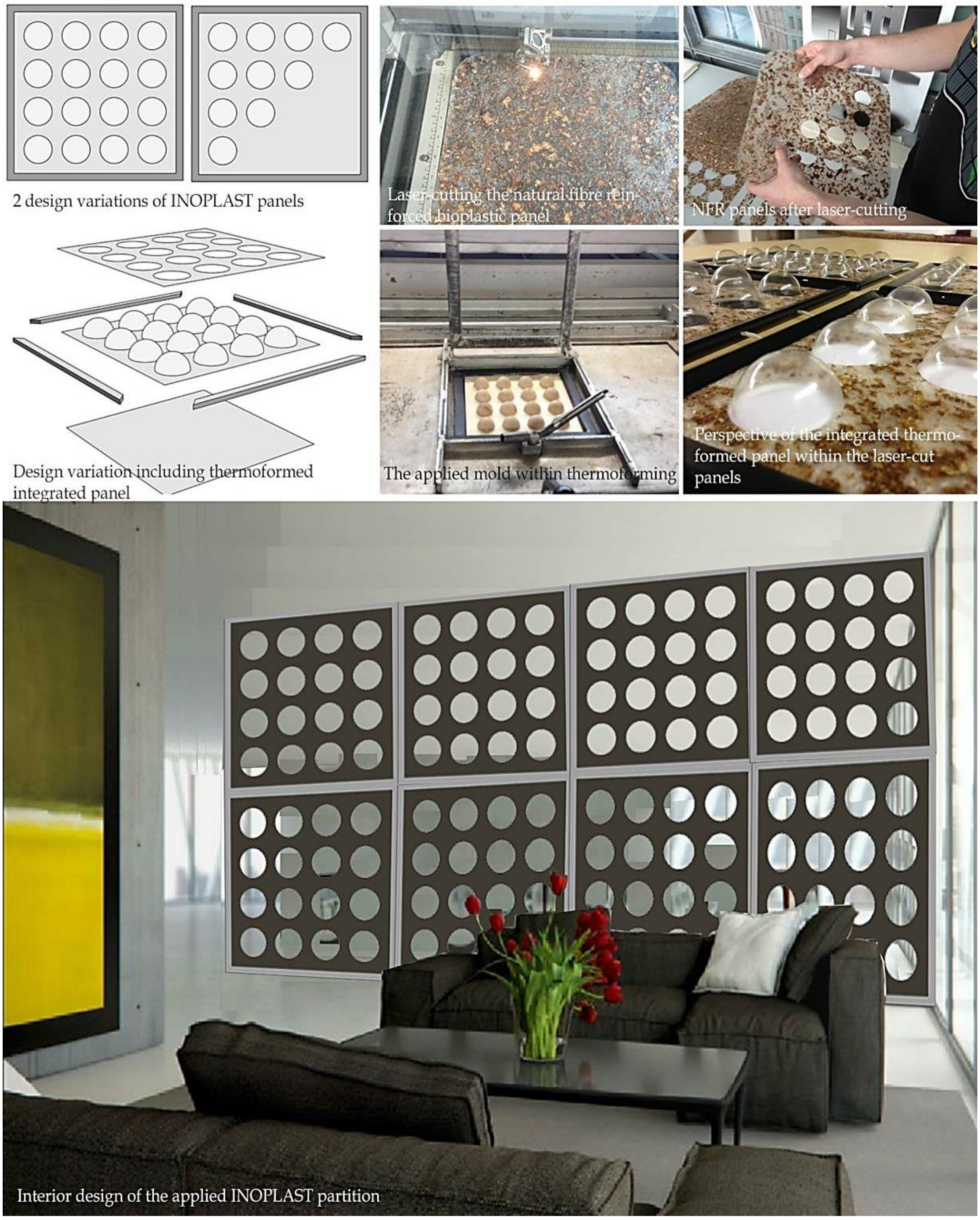
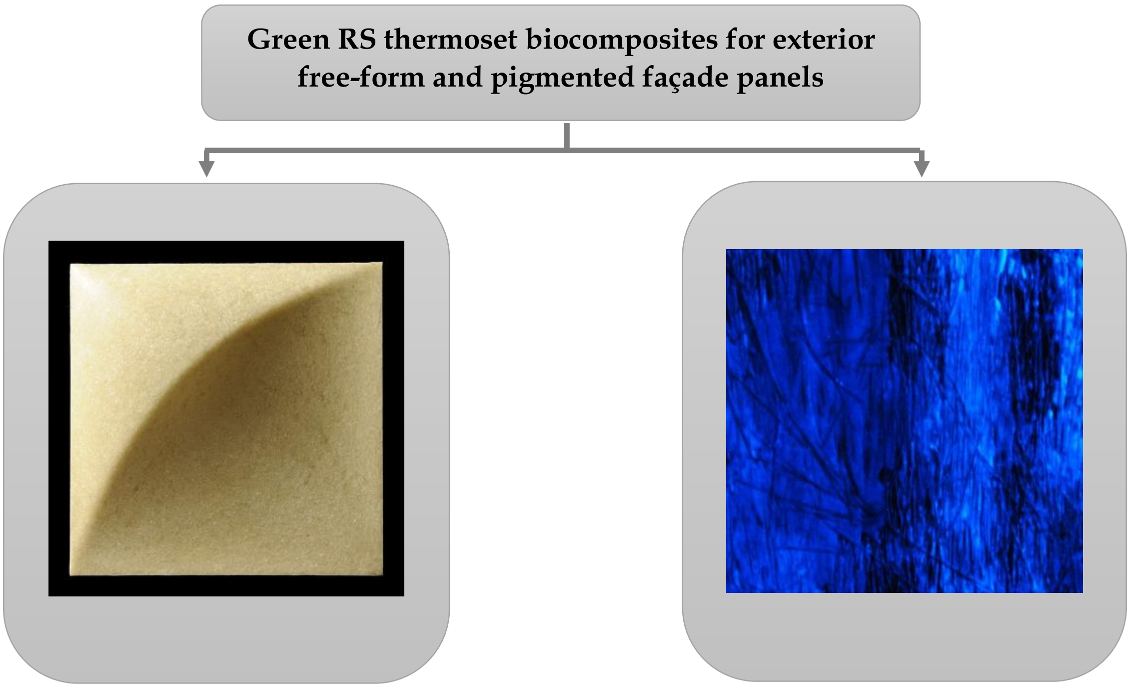


Figure D 2-7.Illustration of two possible variations of applying agrofibre-bioplastic panels in interiors. Photo credit: UP: Student Group, Down: Dahy, H.

[2] This panel's manufacturing was within an educational course supervised by the author. Students participated were: Eugen Grass, Maximilian Fichter, Luca Menghini

D 3. Applications of green rice straw thermoset biocomposites

According to the previous conclusions, the possible applications of the developed green RS thermoset biocomposites, they can be presented as follows for exterior applications:



A number of prototypes were produced to examine the possibility of producing the developed green straw thermoset biocomposites with higher fibre load than that applied in the material development phase illustrated in the last chapter, to investigate the possibility of producing free-form geometries in reality out of the free-oriented short agro-fibres chosen.

Within the following part, two prototypes out of RS-bioresin compositions are illustrated. The green RS biocomposites were prepared from the same selected bioresins applied in the last chapter: Gripox® from Grizzly Leim GmbH and PTP® from B.A.M. (Bio- Composites and More GmbH), but with more fibre load that reached between 40-50% wt., where closed molding techniques were applied in manufacturing. In future work, vacuum assistance should be applied to optimize the process and the surface quality of the final products.

These prototypes are simulating non-structural façade panels, which can be integrated with hidden insulation panels, in the form of rain-screen cladding systems, with enough ventilation gap between the cladding panel and the backward insulation, to allow enough air flow to pass behind the façade cladding panel and prevent possible mold accumulation. The simulation of the fixation method of such cladding elements was applied within the Eco-Pavilion – (see Appendix.)

D 3.1. Free-form façade panel

This mock-up was discussed in a number of conferences and workshops. The description illustrated here is based on (Dahy & Knippers, 2013) and (Dahy, 2013). This panel was manufactured in the form of a free-form shell of 300x300x2-5 mm, manufactured of green RS-thermoset composite, TRAshell[1] , of free-oriented short RS fibre of 50% wt. Other types of agro-fibres including coconut shells and black coal ash as an agro-filler and as a natural pigment were applied in this product design to reach different textures effects. The matrix applied is the bio-resin named Gripox®.

This design is in the form of 2 modules, forming together when combined a free-form elevation. The modules A and B are free-form shells of opposite curvatures, that when combine create a continuous moving line that passes throughout the combined panels.

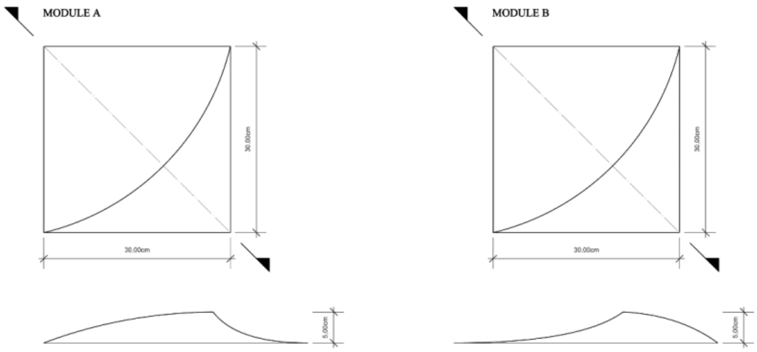


Figure D 3-1. The design of the free-form façade is applied using 2 integrated free-form modules A and B. Photo credit: Student Group

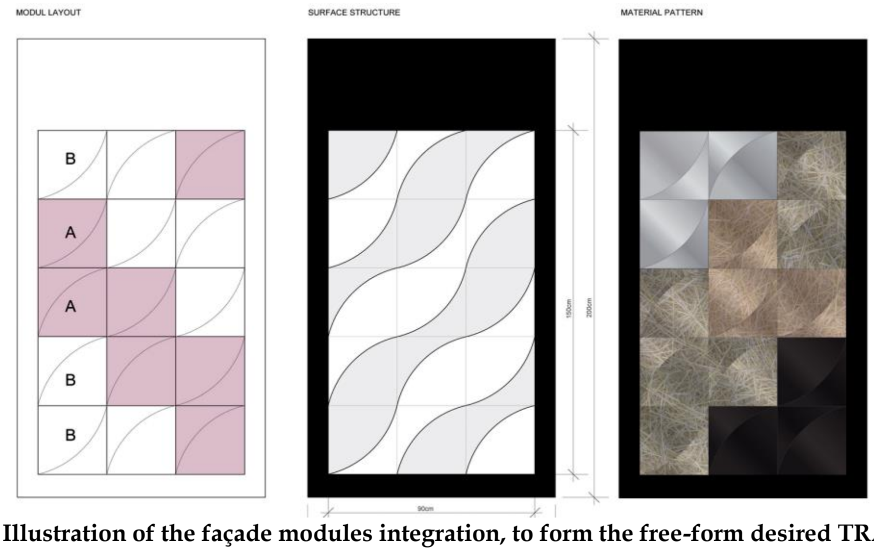
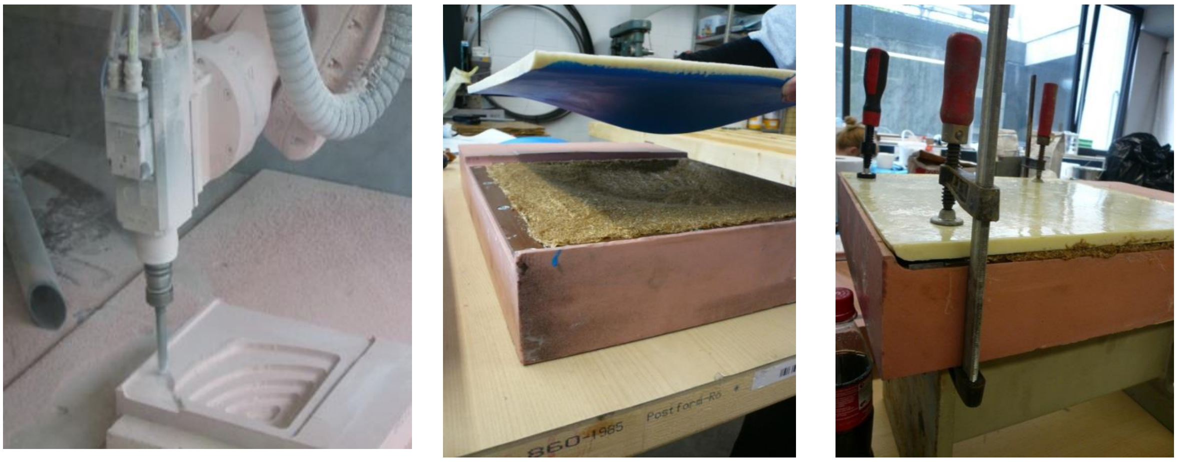


Figure D 3-2. Illustration of the façade modules integration, to form the free-form desired TRASHEL façade panels design. Photo credit: Student Group

The two panels 'contours, representing module A and B, were separately carved after a 3D-model (3D CAD digital drawing), using a robot machine, supplied from the ROBOLAB in the Faculty-1 workshop of the University of Stuttgart. The negative carved molds were made of a

[1] Realized within an educational course, supervised by the author. Students participated in this product: Susanne Hügel, Lousia Scherer, Kerstin Meyer

foam block material (PU 500). The second mold halves, were casted in a separate process to be able to apply the required closed press-molding technique selected to form the free-form designed shells.



The robot-machine carving the negative casting mold, out of (PU 500) foam material.

Covering the mixture within the positive mold-part

Casting the mixture in a closed molding process

Figure D 3-3. Illustration of the drilling and casting process of the TRAshell. Photo credit: Left: Students Group, Middle- Right: Dahy,H.

After mixing the RS with the bioresin, using an electric hand mixer, the mixture was gradually applied in the negative mold using rollers from inside (in the middle of the mold) to outside and in one direction, i.e. non-reversible moving procedures. The upper lid was carefully laid down, over the distributed mixture, then pressed using clamps. Excess resin was released from the mold while pressing, then the casted panel was left for min. 24 hours, at normal room temperature at ca. 23 °C. After 24 hours, the panel was carefully de-molded to complete its further hardening for another minimum 24-48 hours in room temperature.

Different natural pigments and glowing agents were applied to give different design varieties and options of the proposed façade panel designs. Within the mixture, a black color was reachable through the applied coal-ash applied as an agro-filler. In another molding process, colored glowing broken glass pieces, supplied from Fabrino GmbH, that is normally applicable in concrete-based façade panels, were here as well applied for more aesthetic values and UV-resistance. Otherwise, the natural straw and coconut fibres' colors were not changed and left on purpose to reflect the natural components of these developed green composite panels. The double curved panels could be in two opposite directions that would give different design effects, depending on the direction from which the natural lighting comes from, as illustrated in Fig. (D 3-4), that describes the different visual effects of the same panel in different positions.

Module A *Module B*

Figure D 3-4. Modules (A) and (B) settled in 2 opposite positions, to show the possible design variations, that was applied in the 3D-façade, applied in the 'Eco-Pavilion'. Photo credit: B.Milklautsch

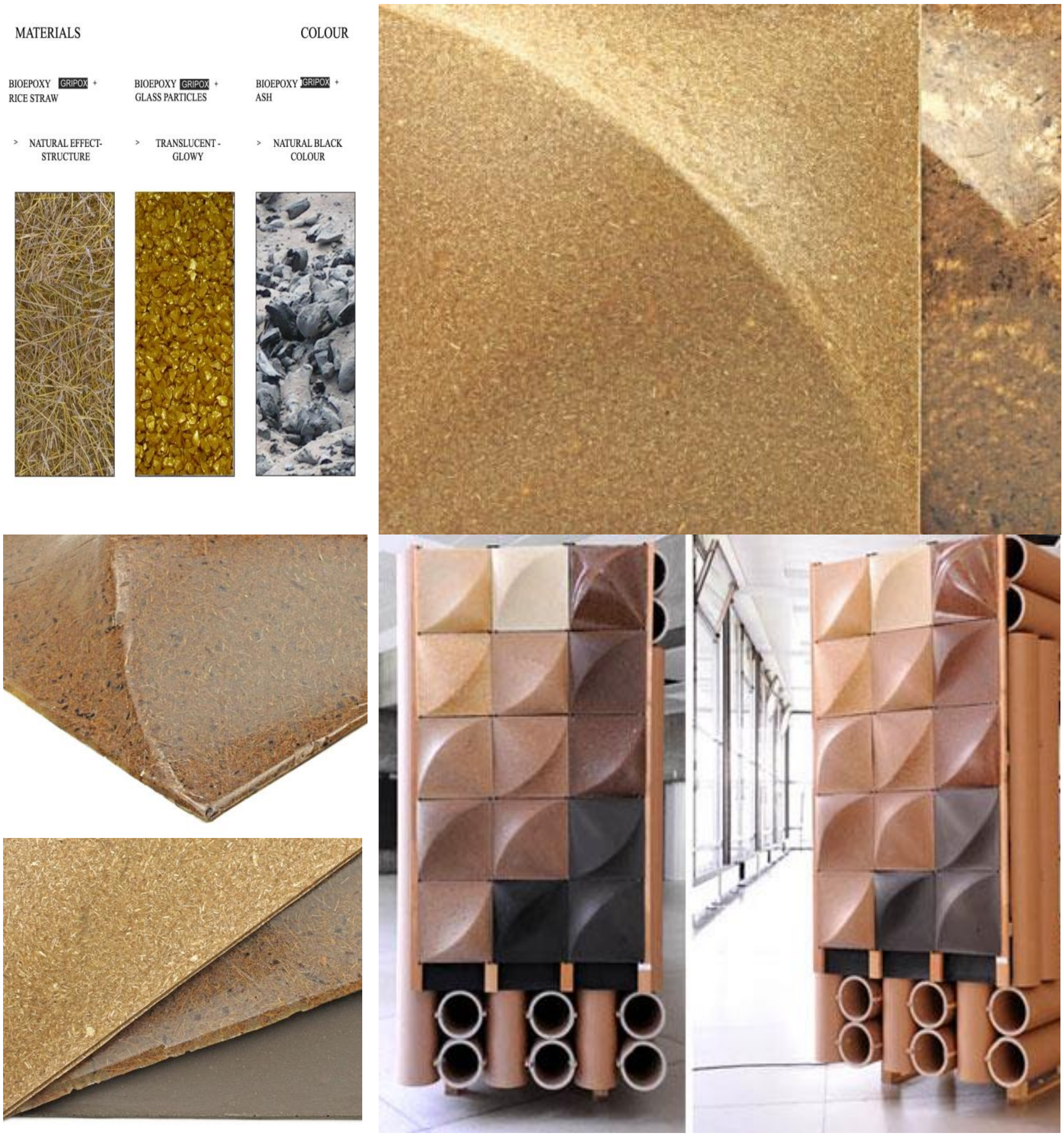
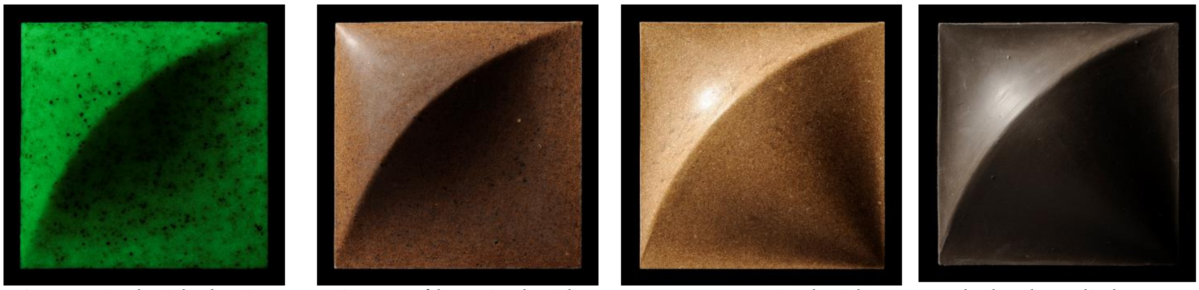


Figure D 3-5. Concept of the applied colors within this panel's design and the final outcome after fixing the panels within the Eco-Pavilion. Photos' credit: raumPROBE OHG and B.Miklautsch.



Straw mixed with glowing glass particles from Fabrino GmbH | *Coconut fibre mixed with Gripox®* | *Raw straw mixed with Gripox®* | *Black ash applied as a pigment*

Figure D 3-6. Illustration of the different coloring effects applied in the TRAshell, depending on the natural color of the raw fibre, glowing particles, or applying black ash as a pigment. Photo credit: B.Milklautsch

D 3.1. Pigmented and laser cut façade panel

This mock-up was also discussed and illustrated in a number of conferences, articles and workshops. The descriptions indicated here is based on (Dahy, 2014) and (Dahy & Knippers, 2013).

The panel is manufactured of pigmented green RS-thermoset composite, of free-oriented short RS fibre of around 50%. The fibres were chopped and mixed with pigmented PTP® bio-resin that was applied in the previous part of this chapter as well, within the proposed developed green biocomposites. The flat panels were laser-cut after an oriental pattern design, BiOrnament[2], composing a panel of 250x250x3-5 mm. The applied pigments were of grey, black and red, which caused extra UV- and weathering- resistance as declared in the previous chapter.

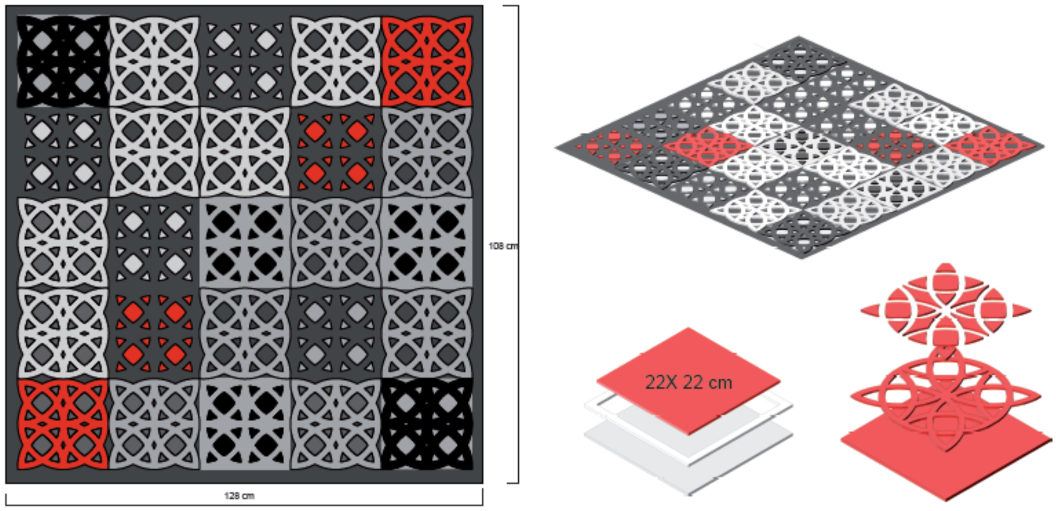
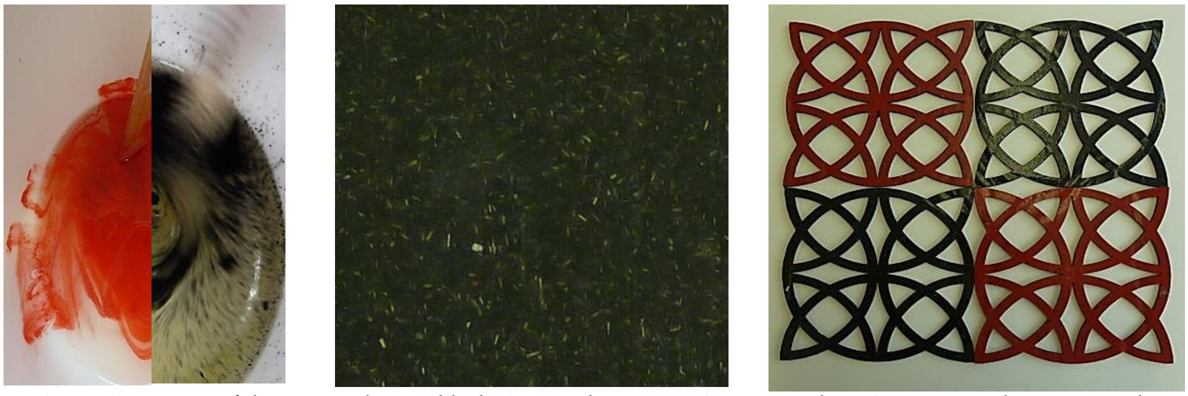


Figure D 3-7. Illustration of the ornamental pattern design according to which the developed biocomposite was laser cut. Photo credit: Student Group

The molds were created from flat metal plates of 250x250x5 mm and wooden frames of 235x15x3-5 mm, and then polished with heat-resistant wax as a release agent. The metal mold was applied to transfer heat easily to the mixture to polymerize, since heat is essential for the hardening process of the selected PTP® bio-resin.

The PTP® bio-resin was prepared after the technical preparation procedures supported by the producer: Biocomposites and More GmbH, then pigments of 2% mass load of the prepared resin was applied; then the chopped straw of 50% mass load of the whole mixture was gradually applied with continuous mixing, using an electric hand mixer. The mixture was divided homogenously within the flat metal mold, and extra trapped air bubbled were rolled out, then the mold was carefully covered with another flat plate and with metal load stocks and was placed in the oven at 130°C for 45 minutes.

[2] Realized within an educational course, supervised by the author. Students participated in this product: Anke März, Gregory Taukhanian, Nora Woborny



Pigmenting process of the resin before adding the fibre | *The pure black pigmented straw PTP® green composite* | *The BIORNAMENT laser-cut panels combined with different coloured patterns*

Figure D 3-8. Illustration of the surface deisgn and colouring possibilities of the BIORNAMENT product design.

The panels produced using the metal plates' mold were successfully de-molded, and were easily cut using a normal wood-cutting wheal machine, before being laser-cut after the ornamental design provided, till 5 mm thickness.

Fixing the board to the pavilion structure. | *The BIORNAMENT panel as applied in the Eco-Pavilion*

Figure D 3-9. Illustration of the BiOnament designed green biocomposite panel, applied as an architectural screen within the constructed pavilion: Eco-Pavilion (see Appendix). Photo credit: Left: Dahy,H.; Right: Miklautsch,B.

Other special pigments and glowing additives could be integrated with the applied environmentally friendly materials and design concepts, to reduce energy costs through selfreflection and illumination. An example on this is this green RS thermoset biocomposite, which is integrated with black light powder as a pigment[3].

Figure D 3-10. Illustration of the green agro-fibre thermoset prototype combined with black light pigment.

[3] Realized within an educational course, supervised by the author. Students participated in this product: Alice Grazzina, Mirjam Müller, Reyhan Toraman

E.

Conclusions & Recommendations

E. Conclusions and Recommendations

E 1. Conclusions

1. Straw is a readily available and renewable fibre-source that can replace wood in fibreboards' making and in natural fibre thermoplastic composites, including WPCs. Inspite of this, straw is still burnt in huge amounts worldwide. The lack of governmental coordination between the farmers and the local industries that depend mainly on natural fibres, including fibreboards' manufacturing and biocomposites, presents the main cause behind straw's accumulation. Stopping the open fields' un-official agro-residues' burning cannot be guaranteed only through regulations and legislations, but rather through real governmental management actions and strategies.
2. The conventional straw application in architecture, straw baling construction, has proven itself in Europe and North America, much more than other high straw producers in Asia, South America and Africa. The main reason is the aesthetic non-attractive value of the straw bales, which led the customers to decline this construction aspect, inspite of its availability, low cost and available technology needed for appliance. Furthermore, the technical drawbacks including thick straw bale-walls' widths, that reach around 40 cm, and the limited stories' number that can be built using this method, was not capable of absorbing the high urban densification needs in these plots.
3. A number of the main straw producers worldwide, including China, USA, Europe, as well as some Asian and South African countries like Japan, Thailand and Brazil, have developed new bio-polymer and bioplastics' production technologies, that should depend in the near future mainly on agro-fibres. Accordingly, this new agro-based bioplastics' technology could be combined with the available straw in these countries to produce a chain of green affordable straw biocomposite products for different applications, including architecture. Applying pure green bio-composites, especially in inner architecture will avoid the risks of VOCs' high presence in interiors and their health risks accordingly. Otherwise, in other countries- where bioplastics' industry are still in earlier phases- like other Asian, African and South American countries, conventional fossil-based polyolefins can be combined with straw, leading to final products' price decrease and replacing the amounts of consumed fossil-based plastics.
4. Applying straw as an active filler in plastics for interior and exterior architectural applications should enable many ecologic and economic advantages including offering a wide range of architectonic designs that would help in increasing the value of applying this abundant fibre in further architectural applications in a wider scale. Agro-plastics' applications in architecture would include mainly non-structural products like doors' and windows' frames, interior and exterior cladding elements, fittings, furniture and others. Binding bioplastics with agro-fibres should raise up many positive environmental values, which are highly demanded in building industry, especially in indoors for safer air-quality.
5. Adding the silica enriched fibre, RS, as an active filler to the PLA and lignin bioplastics separately, caused a complete change in the fire-resistance attitude of the final developed

material. UL 1694 test was applied on the samples with severe testing conditions and a burning time of 20 seconds. RS-PLA was close to be classified and reach UL1694-TC-2, while RS-PP was far beyond classification, wheres RS-Lig. was UL 1694 SC-1 while Cell.-Lig. was not classified after UL 1694. It is believed that if DIN 4102 were applied, RS-Lig. is expected to reach B1 and RS-PLA would reach B3.

6. Classically, in straw composites' making, straw fibre is bleached and the hydrophobic waxy and silica layers are removed to produce a rougher and more hydrophilic straw surface to activate the hydrogen bonding between the hydroxyl groups of straw and the polar groups of the matrices, (Guadalix, et al., 1996), (Ltd, et al., 1999)and (Wasylciw, et al., 1998). In this research, raw straw was applied without chemical treatments to reduce costs, environmental loads and to preserve the natural silica contents, that are here examined throughout the research as a natural flame retardant in the developed biocomposites. Accordingly, RS that has around 20-30 times higher silica amounts than that available in wood, (Wasylciw, et al., 1998), can replace wood flour in WPCs, and can be used as a main eco-additive for flame-retardance in green thermoplastic biocomposites.
7. Viscosity and physical form of the matrix are important factors within the developed RS biocomposites. The selection of the elastic binder in a powder form in addition to its high viscosity and flow, in case of the first developed RS biocomposite, enabled the possibility to encapsulate a large quantity of RS fibre by wt., which could reach till 90%. In case of RS-Lignin, it was clear through the SEM microscopic examination, that the lignin as a matrix was of lower viscosity than PLA and hence could not close the biocomposite's surface properly, the thing that caused the high water-absorption sensitivity. In case of the RS-thermoset biocomposite group, viscosity played a big role as well. Resins of high viscosity were much preferred to facilitate the manufacturing process and to increase fibre fraction's incorporation possibility within the composites.
8. The developed straw fibreboard with the elastic binder (at 80% RS wt.) can be applied without veneering in anti-slippery mats and in sports halls' floorings, due to its high indentation resistance. The abrasive nature of the silica present in the straw should optimize the anti-slippery effect in the flooring mats. Veneering is essential for applying the same fibreboard in free-form furniture and fittings' applications.
9. Within the straw-elastic binder composites at different fibre ratios (from 20-80%), it was noticed that the density increased whenever the fibre load increased till 60% of fibre load, which was opposite to what was expected as the fibre should replace the elastic binder of the higher density, leading to density decrease not the opposite. In addition, at 80% of fibre load, the density decreased again reaching to almost similar value of the composite at 20% fibre load. Therefore, the composites should be re-manufactured in future experimentations to investigate the reason behind this.
10. To evaluate the developed straw-based biocomposites' applications suitability in architectural applications, the technical properties of the RS- thermoplastic and RS-thermoset biocomposites are compared as follows:

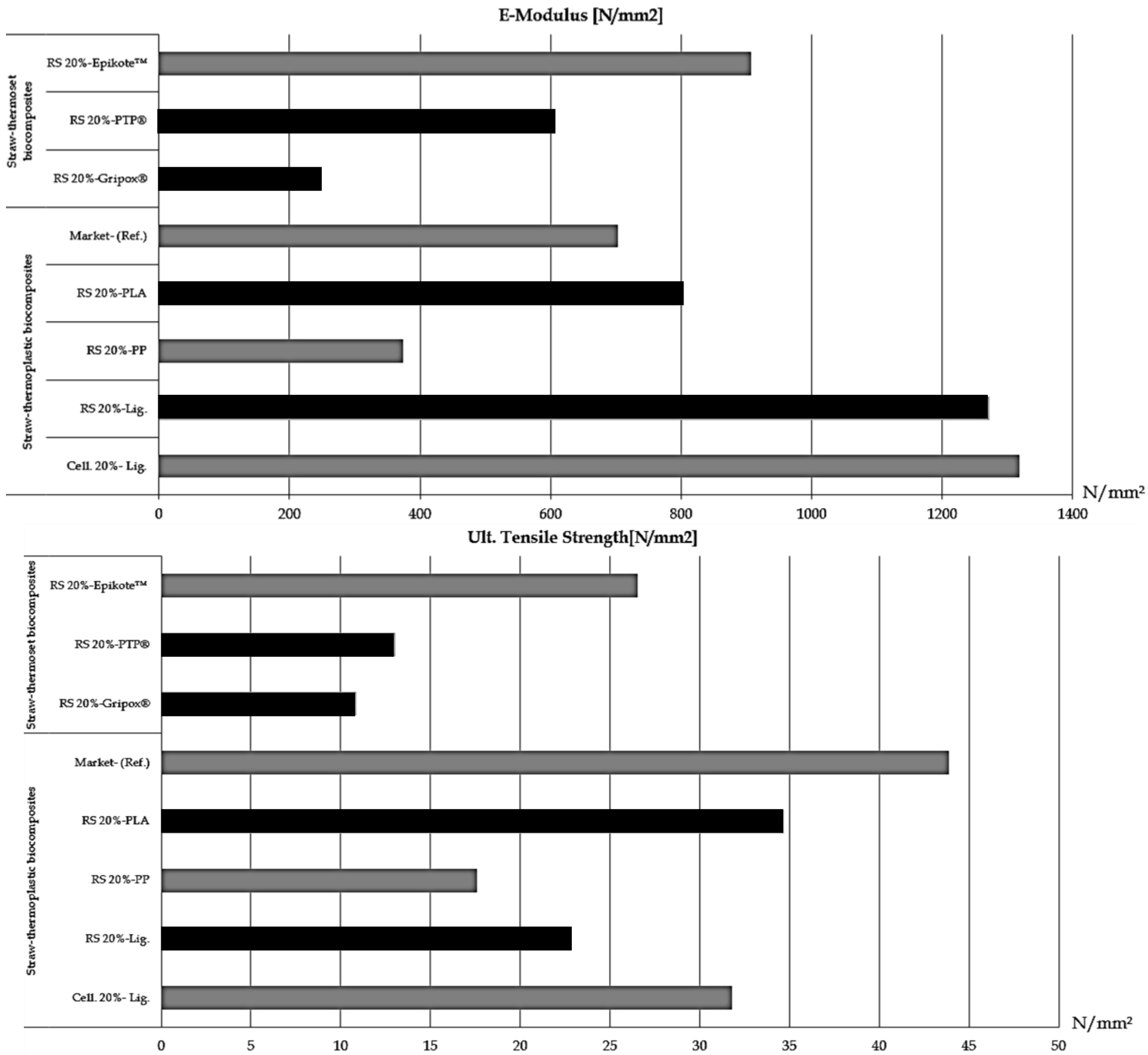


Figure E-1. Comparison of the mechanical properties of the developed RS-thermoplastic and RS-thermoset biocomposites, as well as one of the market green cellulose-thermoplastic composites, referred to as (Ref.)

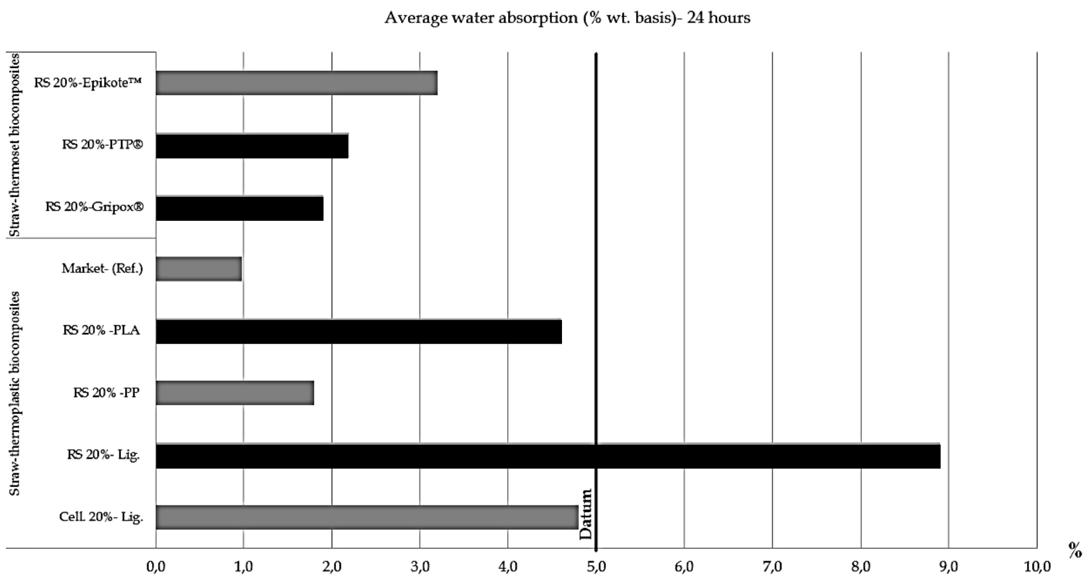


Figure E-2. Comparison of the water absorption mean value of the RS-thermoplastic and RS-thermoset developed biocomposites, as well as two of the market NF-thermoplastic composites, referred to as (Ref.)

Within the RS thermoplastic biocomposites' group, RS-PLA and RS-Lignin have shown much higher mechanical properties than RS-PP. This is in addition to the improvement in the fire resistance of the biocomposites in case of applying RS to bioplastics than that when applied with fossil-based ones, as indicated within the research. Accordingly, the green RS-based biocomposites have high potentials to replace regular fossil-based agro-plastics and WPCs available in the contemporary markets.

Through the previous comparisons, it is clear that generally the mechanical properties of the RS-thermoplastic group are better than that of the RS-thermoset group; while the water sensitivity is higher in case of the RS-thermoplastic group, especially in the case of RS-Lignin biocomposite.

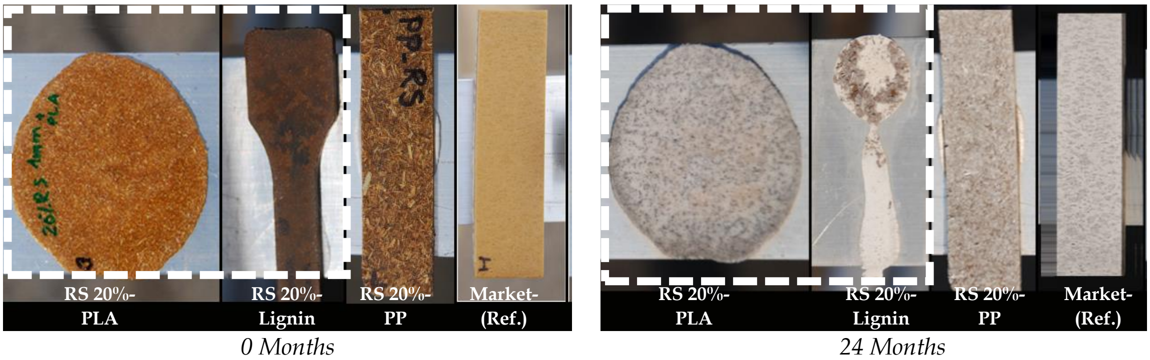


Figure E-3. Comparison between the developed RS-thermoplastic composites before and after 24 free-weathering months

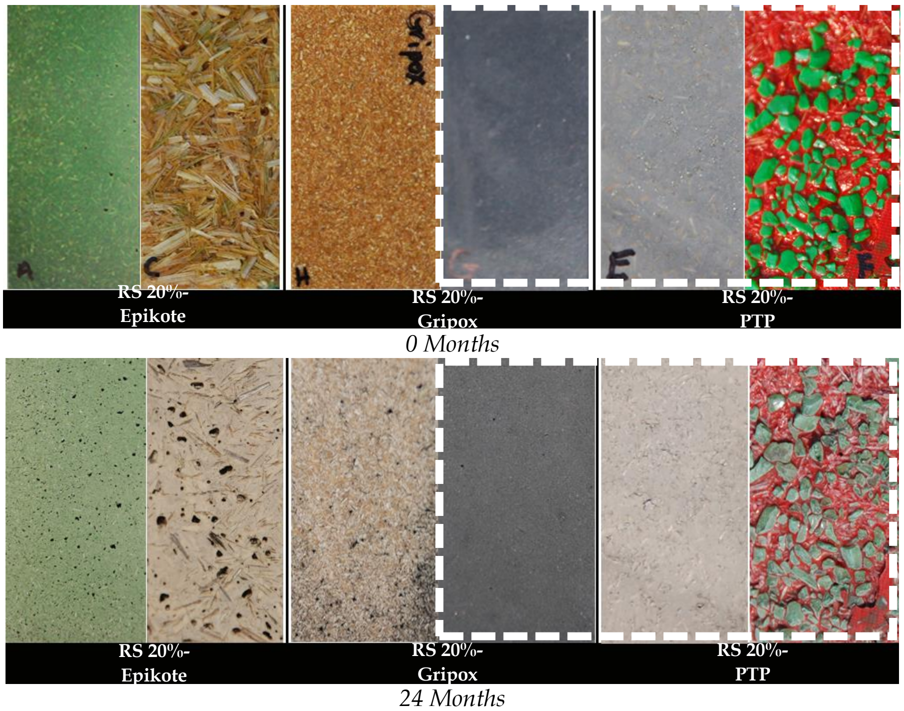


Figure E-4. Comparison between the developed RS-thermoset composites before and after 24 free-weathering months

Regarding free-weathering, RS-thermoset group was more resistant to weathering than the RS-thermoplastic group, especially in combination with pigments, as illustrated in Fig. (E-4), that could enable them to be applied as non-structural façade screens, after further developments concerning fire-retardation. However, this should be assured through re-testing the mechanical performance of the biocomposites after weathering, which did not take place in this research.

As illustrated through the previous figures and the analysis in Chapter C, the technical, economic and ecologic properties' comparison between the two developed green RS-based biocomposite groups, can be shortly expressed as follows:

Technical Properties (at RS 20% wt.)	**Green RS- thermoplastics**	**Green RS- thermosets**
Densities [g/cm^3]	1,2-1,3	1,07- 1,1
Water Absorption	+ -	+
Mechanical Properties	+	+ -
Compatibility and fibre/matrix interface	+	+ -
Natural Weathering	-	+
Fire Resistance	++	-
Ecological Assessment – Recycling- Compostability- Carbon footprint	+ +	+ -
Cost- Material	+ -	++
Cost- Processing	++	-

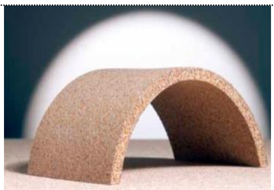
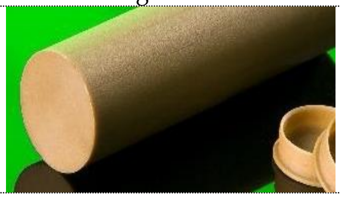
Legend: (-) : bad, un-reasonable, (+) : good, reasonable

Table E-1. Comparison in the advantages and disadvantages of the two developed green RS-based biocomposites.

Through the previous comparisons and illustrations, it is clear that green RS-thermoplastics enjoy much better technical properties, than the RS- thermosets, especially regarding the mechanical properties, compatibility, fire-resistance and ecological assessment, which promote their appliance possibilities in architectural applications much more than the other green RS-thermoset group, especially in interior applications. However, regarding the high processing costs of the green RS-thermoplastics, green RS-thermosets could be of higher preference when pigmented and applied in exterior applications with complex geometries, especially that they still have the ability to be incinerated at the end of its useful life-time releasing the same carbon dioxide once absorbed by the plant-based green biocomposite components.

11. As indicated, straw-thermosets are generally recommended in architectural applications, in case of complex forms' needs that would be too expensive to be achieved with agroplastics, due to the high processing costs. That's why some agro-thermoset products have newly emerged in the contemporary markets, to cover the complex geometrical forms' aspect in specific with higher economic as well as ecologic feedback, like Organoid® as previously discussed in Chapter B.
12. Throughout the research, five RS-based biocomposites have been developed including a fibreboard with an elastic binder, two green RS thermoplastic biocomposites and two green thermoset biocomposites. The elastic RS fibreboard, resembles in its form and applications' scope an available market material, named Recoflex®. In addition, the

developed green RS lignin biocomposite shares the same concept of the green cellulose-lignin market product, Ecogehr®-CL. While, the developed green straw-based epoxy biocomposite's cladding elements, have the same concept and application possibilities of the market product Duralmond®. Those available products, which the developed RS-based biocomposites could replace, are hereby given through the following table, to evaluate their advantages and drawbacks.

Product Category	Elastic fiberboards	Natural fibre thermoplastic biocomposites	Natural fibre thermoset biocomposites
Product Name	Recoflex®	Ecogehr®-CL	Duralmond®
Photo			
Photo credit	(BSW BerleburgerSchaumstoff werk GmbH, 2013).	www.modernplastics.com	www.decke-wand-boden.de
Price/m²	x- 5 x	8 x - 32 x	12 x – 13 x
Main Components	Wood and cork mixed with latex and polyurethane mixtures	Hemp and cotton cellulose fibres of around 30% mixed with plasticized lignin and additives	Crushed almond shells combined with a mixture of resins
Advantages	Free-form architectonic designs	Recyclable- No/minimal emissions - Biodegradable	Free-form architectonic designs
Disadvantages	Based on slow renewable materials (wood) in comparison to the annual straw and expensive slow-renewable natural materials (cork)	expensive	Non-recyclable - expensive

The prices are symbolized in x, relative to their actual prices collected from (Pohl, C.- Berleburger Schaumstoffwerk GmbH, 2014) for Recoflex®, (Grainger Industrial Supply, W.W.Grainger, Inc., 2011) for Ecogehr® - CL and (StoneslikeStones GmbH, 2013) for Duralmond® between 2011 and 2014

Table E-2. Illustration of the available market products that could be replaced through the suggested straw-based biocomposites.

It is clear through the previous table that the high prices are the main drawback of the available biocomposites in the contemporary market, in addition to the dependence on slow and expensive renewable resources. Accordingly, the developed straw biocomposites could highly compete in the contemporary markets depending on the expected reasonable end-product's price and its appropriate technical characteristics, especially regarding the fire-resistance behavior.

E 2. Recommendations for future research work

1. More governmental coordination should take place to cover the trip between the farmers and the natural fibre-based industries. Storage units and densifying facilities should be located next to the farms to guarantee densified straw's availability all over the year.
2. Different types of other agro-fibres are recommended to be applied in future work to manufacture similar biocomposite materials and to compare them with the ones developed in this research. Wheat Straw (WS) should be capable of replacing RS in all the biocomposites developed in this research, depending on the morphological and chemical similarities between the two natural fibres, giving almost the same technical performance. However, in case of WS-bioplastics, fire-resistance performance should be checked if it would give the same results as in case of RS appliance or not, since WS has less silica in its tissues than that of RS.
3. It is recommended to apply cereal straw with its natural humidity as a physical foaming agent, which is an environmental-friendly method that can replace the un-healthy chemical foaming agents within natural fibre reinforced foams and biofoams developments. Through this technology, much lighter weights and higher thermal insulation properties could be achieved using recyclable ecological friendly and affordable materials.
4. In future work, within this context, coupling agents like maelic anhydride should be applied to optimize the mechanical behavior of the developed biocomposites. However, the biocomposites' flame-resistance behavior should be investigated if it would be affected or not.
5. In future work, the developed elastic straw fibreboards should be treated with silane coupling agent during the compounding process, to improve the water absorption sensitivity.
6. It was illustrated within Chapter C, how promising the RS-PTP® thermoset biocomposite is, in respect to technical properties, weathering resistance and expected price. However, it is recommended for this material to be further developed in respect to fire resistance behavior, through adding appropriate fire-retardant additives or through increasing the RS mass-content and in this case re-evaluation of its fire-resistance behavior should take place.
7. The developed materials' mechanical properties should be re-tested after weathering, to evaluate loss or change of the properties, which did not take place in this research.
8. The low weathering resistance of the green RS-thermoplastic group could be improved in future work through stabilizers and UV-resistance additives; while water absorption could be optimized through applying coupling agents that should improve the fibre/matrix interface, hence improving bonding and preventing water molecules from escaping inside the materials' bodies.

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Photos

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Appendix

X. Appendix- ECO-PAVILION

X 1. Concept of the applied built pavilion: the 'Eco-Pavilion'

It was desired to simulate the possible applications of the developed straw biocomposites in a pavilion form that translates in a 1:1 scale the different straw applications' possibilities and potentials in architecture in a different method than the classic straw bales, discussed in chapter 2.

Accordingly, a pavilion of 4.00x1.08x2.00 m, was built and exhibited in the interior foyer of the faculty of Architecture of the University of Stuttgart in Germany, then transported to be proposed once more in Erdmannhausen in another exhibition entitled: Ökomesse.

The main simulation concept can be expressed through the following sketch, which illustrates the different application possibilities of the straw biocomposites in the interior and exterior non-structural applications in buildings. This includes interior and exterior free-form cladding systems, interior partitions, flooring systems, anti-shock mats, as well as free-form furniture and interior fittings.

Construction phasing took place within a seminar work supervised by the researcher, in cooperation with 'Architektur Grosse Büro', an architectural office, in Stuttgart and in common work with 20 architectural students and the sponsorship of a number of companies including Hoffmann GmbH, Müller GmbH, Momentive GmbH, Gehr GmbH, Reckli GmbH, Wacker Chemie AG, Fabrino Produktionsgesellschaft GmbH & Co. KG and ISOCELL GmbH. In addition a number of educational organizations in Stuttgart supported this work through their workshops and machines including: University of Hohenheim – Institute for Agricultural Technology, University of Stuttgart- Institute for In-organic Chemistry, Stuttgart's State Academy of the Fine Arts- Weißenhof, Akaflieg Stuttgart: Akademische Fliegergruppe Stuttgart e.V. and HFT-Hochschule für Technik, Stuttgart.

The first conceptual sketches seen within the next figure describe the main theme of the prototype and the type of target applications and products that were needed to be developed mainly from the specified agro-residues' fibres' resources, in collaboration with other products from other specified residues' types.

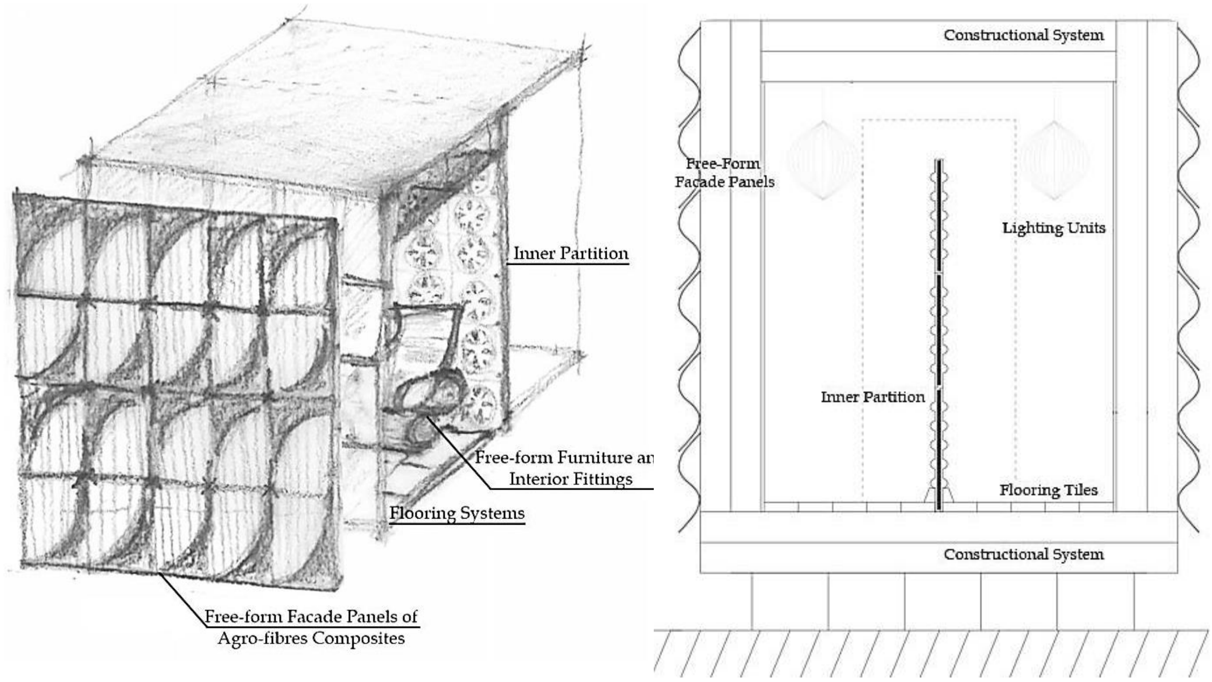


Figure X-1. Primary sketches illustrating the applications' possibilities of the developed straw biocomposites within the 'Eco-Pavilion'

X 1.1. Structural Skeleton

Since the desired outcome was meant to simulate the possible sustainable applications in architecture that are based of solid residues, the selected structural elements of the pavilion was chosen to be from the solid waste stream as well, which is old paper.

The structural cartoon tubes were settled to have an external diameter of 18 cm, bonded by special wooden connections in a dry form, to guarantee the possibility of dismantling the structural components and re-using each item separately, after the end of the exhibition time. This was another sustainability aspect that was put into consideration to decrease the CO_2-footprint of the pavilion to the minimum. The cartoon pipes were sponsored by the company: Kartonagen Müller GmbH, and the wooden combining elements were designed by Hr. Grosse and sponsored from the company: Hoffmann GmbH.

X 1.2. Conception of the developed products' applied in the pavilion

The concept of developed products was based on developing different architectural solutions and applications from re-used and re-cycled agro-fibres from the agricultural waste stream, in addition to other integrated materials from other waste streams, including mainly old paper and old plastics from the solid municipal waste stream. The developed products included different applications' possibilities like: Façade cladding rain-screen elements, inner cladding elements, hanged interior screen, false-ceiling elements integrated with back-lighting solutions, as well as flooring systems. The products were mostly previously indicated through the research, between straw thermoplastic, thermoset and elastic composites, in addition to other composites similar to Papercrete™ conceptions of old paper and cement combinations, which were applied here in this pavilion as lightweight flooring tiles.

X 1.3. Simulation of recycled thermal insulation applied in the pavilion

The thermal insulation was pre-formulated out of recycled fibrillated cellulose, provided from ISOCELL GmbH and milled-wood rest, collected from the wood workshop of the faculty of Architecture of the University of Stuttgart. The fibrils were mixed with paper glue and were molded within an open mold, formed through combining two cartoon columns, to suit the application afterwards, between the pavilion's cartoon pipes.

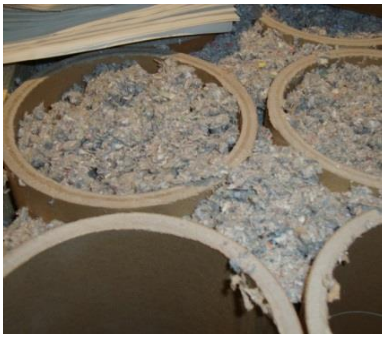
1- Mixing the fibrils with the glue

2- The mixture shouldn't be extra humid

3- Applying the mixture in the mold

4- The molded insulation should be compact and dense

5- Releasing the molded insulation for de-hydration



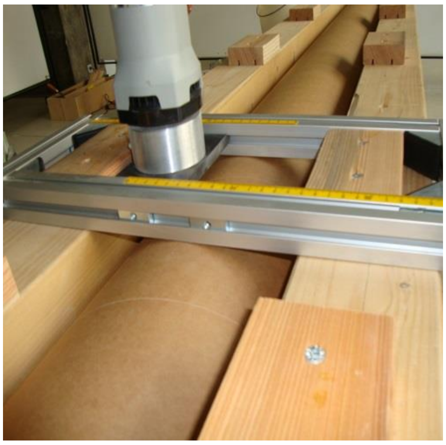
6- Possibility of filling the hollow coloumns with cellulose insulation for passive housing applications

Figure X-2. Illustration of the steps applied to create the low-cost thermal insulation that was installed in the pavilion to close the round gaps between the cartoon coloumns and to provide insulation

X 2. Building phase of the structural elements

The cartoon pipes were drilled and special slots were created in the cartoon pipes' bodies as indicated in the following figures. The drilled slots were prepared so that the wooden connectors would be infused in between those slots, causing proper fixation to take place between each 2 cartoon pipes, without the need of using wet gluing or fixed connections.

Fixing the cartoon columns in the wooden frame to guarantee fixation during the drilling process

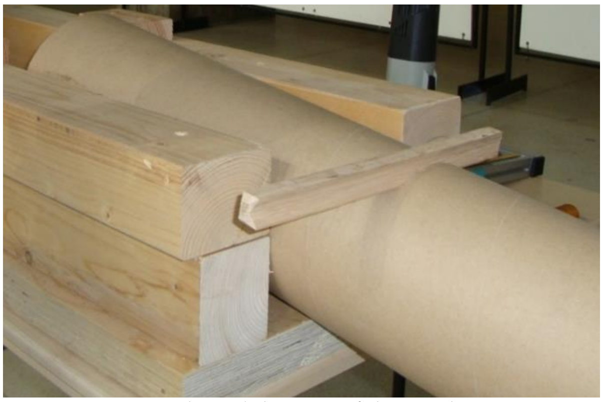


The drilling machine fixed onto the wooden frame above the cartoon column, prior to each drilling process

Drilling process taking place according to defined distances, to be ready for the dry fixation process through the wooden dove-tails

Figure X-3. Illustration of the drilling activities as a preparation process of the cartoon constructional pipes, prior to installation processes.

The wooden connectors were first set in a number of the cartoon pipes' drilled slots, to ensure stability. Afterwards, the building phase started taking place through fixing the bottom of the pavilion, then lifting this base on wooden pallets. The pavilion's sides, simulating the building's walls were then fixed to the base, using the same wooden connectors' fixation method. The top of the pavilion was hand-lifted after pre-fixing parts of it, then fixed with the rest of the pavilion's body. Through the following figure, this sequence of the construction's building phase is illustrated.



1-Experimenting the stabilization of the wooden connectors within the drilled slots in the cartoon pipes

2-Elevating the bottom on wooden plates to keep away from natural floor humidity

3-Fixing the base with the side walls

4-Preparing the other wall separately before fixing it to the finished parts of the pavilion

5-Digging in the wood connectors

6-Balancing the elevated sides before hand-lifting the ceiling

7-Fixing the ceiling to the structure to the body

8-Completing digging the wooden connectors

Figure X-4. Illustration of the structure's preparation, fixation and construction procedures

X 3. Developed products' fixation

Each developed product was individually fixed to the pavilion's selected structure that should simulate the fixation possibility of those products when applied in classic building types, indoors or outdoors.

The BiOrnament was here applied as an inner cladding system, and was the first product fixed in the pavilion through previous fixation on a black background then screwing it directly to the cartoon structure, as here indicated:

Screwing the BiOrnament onto the back-construction

BiOrnament panels fixed as inner cladding system

Figure X-5. Illustration of the BiOrnament fixation in the Eco-Pavilion

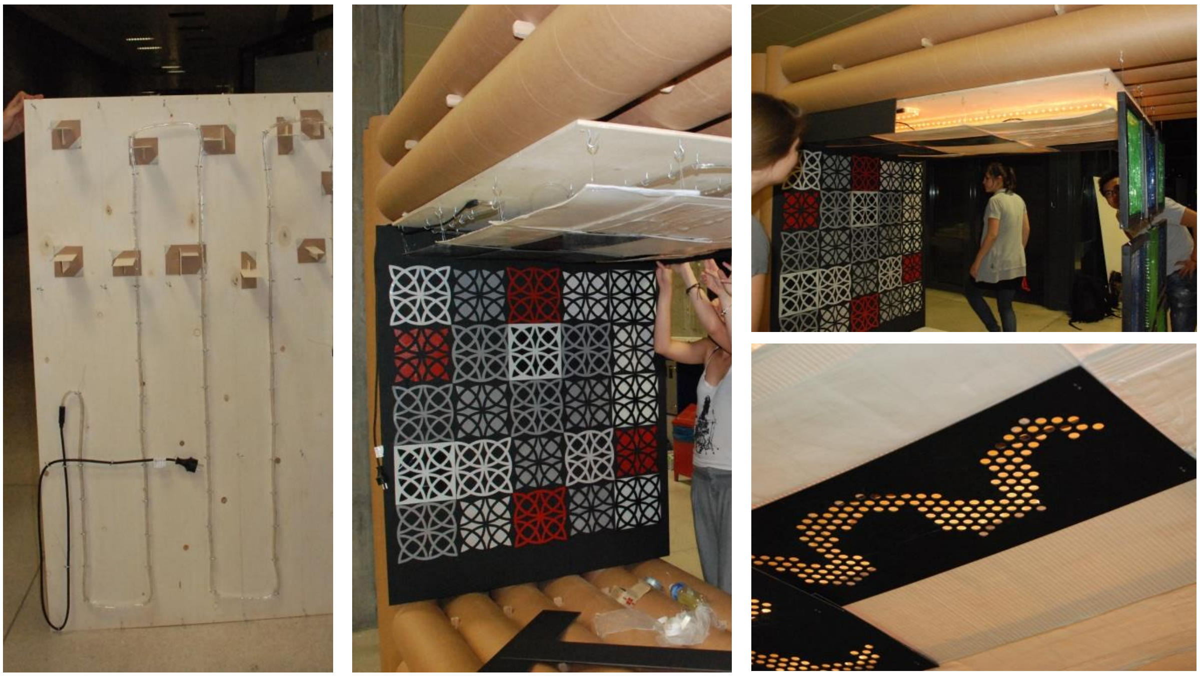
The Plant CULTURE and STRAWAVE were drilled and screwed separately within the inner partitions as cladding systems

Screwing the STRAWAVE panels after drilling them

Drilled and screwed PlantCULTURE panels

Figure X-6. PlantCULTURE and STRAWAVE panels fixed as interior cladding panels in the Eco-Pavilion

The false ceiling Eco-Mask units were then fixed through the pre-installed screws. A lighting system was fixed at the back-side of the panels as illustrated.



The lighting unit were pre-fixed on a separate panel

Hanging the Eco-Mask tiles using hooks fixed to the backward-construction

The Eco-Mask tiles with the laminated lighting units

Figure X-7. Illustration of the Eco-Mask tiles, hanged as false ceiling with integrated backward lighting

The 'Ecotiles' was the suggested product name manufactured from old paper and cement mixtures, molded within the Reckli® rubber matrices, forming the applied flooring panels within this pavilion. They were simply laid on the surface of the bottom of the pavilion. RS fibreboard with elastic binder, which was developed in Chapter C, would substitute in this case the bottom surface of the flooring elements, as illustrated within the application possibilities of the elastic RS fibreboard described in Chapter D.

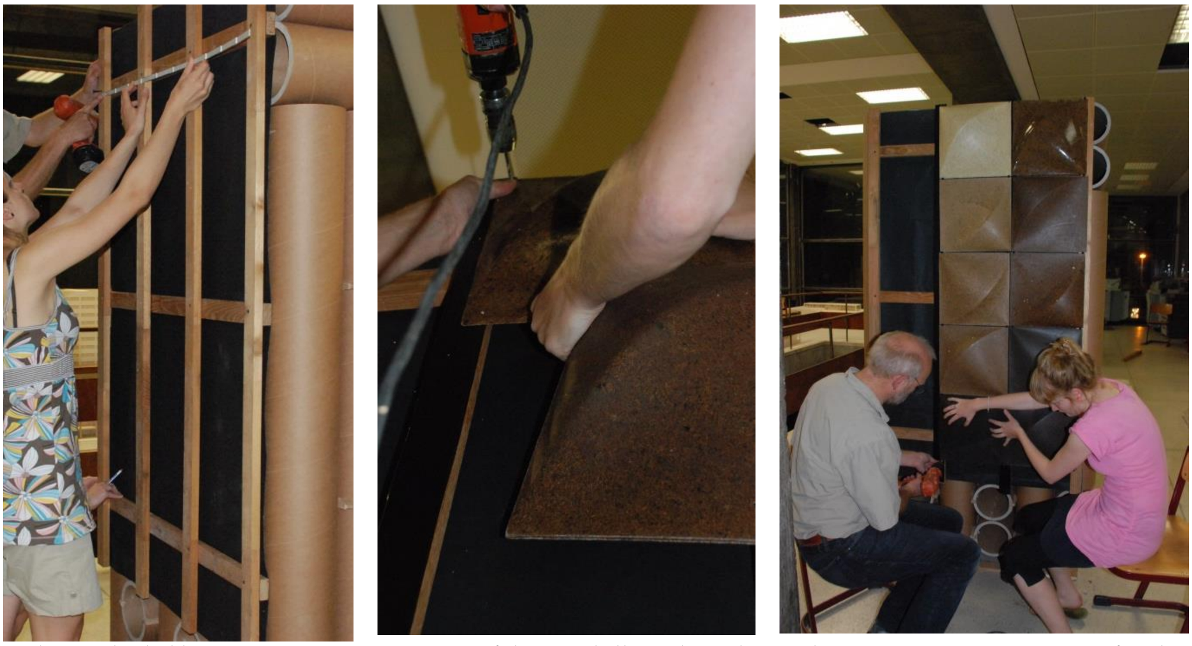
The TRAshell façade panels were fixed in the same possible method of façade rain-screen cladding elements. Within the applied construction system, the following interior and exterior cladding systems could be fixed as follows:

Simulation of the façade panels' fixation possibilities with the installed insulation within the back-construction

Simulation of the interior cladding fixation possibility onto the back-cartoon pipes' construction, applied in the Eco-Pavilion

Figure X-8. Illustration of the interior and exterior cladding possibilities applying the construction system used in the Pavilion, from the 'Leben in Karton'-Gallery Stihl 2010.

Similarly, the developed TRAshell façade panels were fixed after providing back-construction system, as follows:



The wooden hidden construction fixed to the cartoon pipes prior to panels' fixation

Fixation of the TRAshell panels on the wooden construction, as rain-screen façade panels

Figure X-9. Illustration of the TRAshell panels' fixation on the Eco-Pavilion's exterior elevation as a façade rain-screen application.

The hanged inner partition was developed from re-used plastic bottles that were transformed into threads and combined in the form of panels, which were integrated with an interior lighting system, and hanged from upwards and downwards with hooks fixed to the ceiling and the flooring's structure of the pavilion.

Hanging the inner partition using hooks

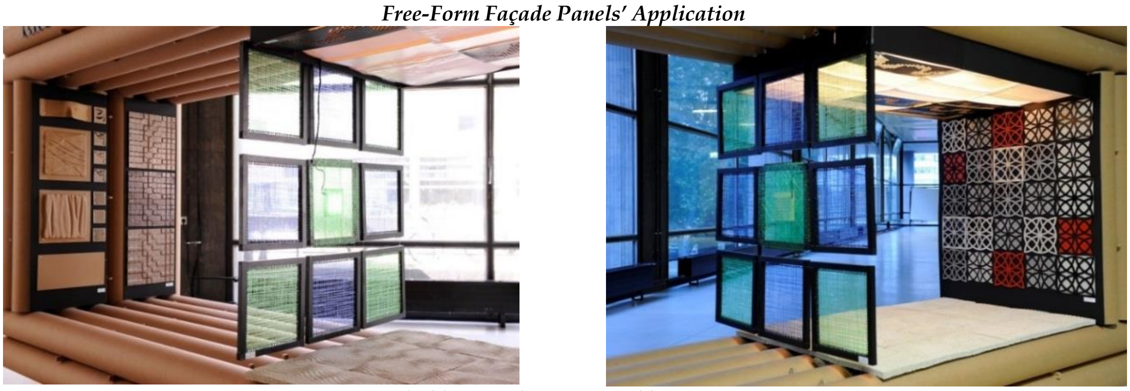
The inner partition with integrated lighting

Figure X-10. Illustration of the hanged inner partition within the pavilion

X 4. Final Outcome

Within this prototype, an experimental simulation for the developed materials with different architectural designs was applied. These simulations were applied in a 1:1 scale to experiment the possibilities of producing the developed materials in the form of real designed products, starting from a product-design concept as thoroughly discussed in the previous chapters, till the realistic application possibility.

Free-Form Façade Panels' Application



Interior cladding applications and hanging partition

Integrated lighting applications within the false-ceiling

Figure X-11. Illustration of the Eco-Pavilion with the developed products' applications possibilities. Photos' credit: Miklautsch, B.

Technisches Datenblatt
ECOGEHR CL® natur[9)]

I. Allgem. Eigenschaften[1)]

	Norm	Einheit	Wert
1. Dichte (ρ)	ISO 1183	g/cm³	1,28
2. Wasseraufnahme	ISO 62	%	2,5
3. Feuchtigkeitsaufnahme			-
4a. Dauergebrauchstemperatur obere	UL746B	°C	65
4b. Dauergebrauchstemperatur untere			-

II. Mech. Eigenschaften

	Norm	Einheit	Wert
1. Streckspannung (σ_S)	ISO 527	MPa	35
2. Streckdehnung (ε_S)		%	1,1
3. Reißfestigkeit (σ_R)		MPa	35
4. Reißdehnung (ε_R)		%	1,2
5. Schlagzähigkeit (a_n)	ISO 179	kJ/m²	13
6. Kerbschlagzähigkeit (a_k)			2,8
7. Kugeldruckhärte (H_k) / Rockwell	ISO 2039	MPa	-
8. Shore-D	ISO 868		-
9. Biegefestigkeit ($\sigma_{B\,3,5\,\%}$)	ISO 178	MPa	-
10. Elastizitätsmodul (E_t)	ISO 527		4250

III. Therm. Eigenschaften

		Norm	Einheit	Wert
1. Vicat-Erweichungstemp.	VST/B/50	ISO 306	°C	-
	VST/A/50			-
2. Formbeständigkeitstemp.	HDT/B	ISO 75		53
	HDT/A			-
3. Längenausdehnungskoeffizient (α)		ISO 11359	$K^{-1} * 10^{-4}$	-
4. Wärmeleitfähigkeit bei 20 °C (λ)		ISO 22007-4	W/(m*K)	-
5. Glasübergangstemperatur (T_g)		ISO 3146	°C	-
6. Kristallit- Schmelzbereich (T_m)				-

IV. Elektr. Eigenschaften

	Norm	Einheit	Wert
1. Spez. Durchgangswiderstand (ρ_D)[8)]	IEC 60093	Ω*cm	-
2. Oberflächenwiderstand (R_o)[8)]		Ω	-
3. Dielektrizitätszahl bei 1 MHz (ε_r)	IEC 60250	-	-
4. Diel. Verlustfaktor bei 1 MHz (tanδ)		-	-
5. Durchschlagfestigkeit	IEC 60243-1	kV/mm	-
6. Kriechstromfestigkeit	IEC 60112	V	-

V. Weitere Angaben

	Norm	Einheit	Wert
1. Klebemöglichkeit	-	-	+
2. Physiol. Unbedenklichkeit [5)] gemäß	EEC	-	-
	FDA	-	-
3. Brandverhalten	UL 94	-	-
4. Sauerstoffindex	ASTM D2863	%	-
5. UV-Beständigkeit[6)]	-	-	-

1) Diese Werte wurden von Fachleuten erstellt und enthalten unsere derzeitigen Erfahrungen. Sie können deshalb in hohem Maße als anwendbar bezeichnet werden, ohne für jeden Fall der Anwendung verbindlich zu sein. Am Fertigprodukt können einige dieser Eigenschaften von diesen Werten abweichen, zumal diese Werte durch Mittelwertberechnungen, an aus gerade produzierten Halbzeugen (ø 40-60 mm) hergestellten Probekörpern ermittelt wurden. Es handelt sich hier um Richtwerte und nicht um zugesicherte Eigenschaften und sollten demnach nicht für Spezifikationen herangezogen werden. Bei fehlenden Messwerten wurden, soweit diese vorlagen, die Daten der Rohstoffe herangezogen.
2) Vorbehandlung notwendig 3) 65 (Vollstab 160 - 200 mm ø) 57 (Vollstab 220 - 300 mm ø)
4) 59 (Vollstab 160 - 200 mm ø), 51 (Vollstab 220 - 300 mm ø) 5) Physiologische Unbedenklichkeiten gelten i.d.R. für naturfarbene Materialien und wurden an den Rohstoffen ermittelt. Zulassungen für die Halbzeuge sind teilweise ebenso vorhanden, oder in Vorbereitung. Bitte klären Sie dies mit uns separat. 6) Gilt für naturfarbene Materialien. Eine zusätzliche Lichtschutzwirkung können gewisse Pigmente, z.B. Ruß, übernehmen. 7) Prüfergebnisse ohne UL-Registrierung 8) Daten gelten für naturfarbene Werkstoffe 9) Daten vom Rohstoff entnommen
* Eigeneinschätzung ohne Prüfzeugnis
o.B.= ohne Bruch + = ja o = bedingt - = nein/keine Daten vorhanden

Änderungen vorbehalten. Seite 1 von 1 Stand: 13/10

INFORMATION

BSW

Produktinformation

Recoflex® 280, 4 mm

Überarbeitungsdatum: 20.08.2013

Druckdatum: 08.01.2015

1. Anwendungszweck	Elastik - Basismatte für Sporthallenböden		
2. Produkt	Produktname	: **Recoflex® 280**	
	Farbe	: holz-ähnlich	
	Material	: PUR-gebundene Matte aus Holz-, Kork- und Latexanteilen	
	Abmessung	: 4 mm	
3. Technische Daten	Raumgewicht	: 270 kg/m³	
	Flächengewicht	: 1,08 kg/m²	
	Zugfestigkeit	: 0,23 N/mm²	in Anlehnung an DIN EN ISO 1798
	Reißdehnung	: 25%	in Anlehnung an DIN EN ISO 1798
	Druckspannung bei 25% Verformung	: 0,25 N/mm²	DIN EN ISO 3386-2
	Kraftabbau	: 23%	DIN 18032, Teil 2
	Temperaturbeständigkeit	: - 40° C bis 115° C	
	Brandverhalten	: Klasse E	DIN EN 13501-1
4. Anmerkung	Unsere Beratung erfolgt nach bestem Wissen, gilt jedoch nur als unverbindlicher Hinweis und befreit nicht von der eigenen Prüfung der von uns gelieferten Produkte auf ihre Eignung für die beabsichtigten Verfahren und Zwecke. Die angegebenen technischen Daten sind Richtwerte, d. h. Erfahrungswerte aus längeren Produktionszeiträumen. Die Verarbeitung unserer Produkte erfolgt außerhalb unserer Kontrollmöglichkeit und liegt daher ausschließlich in Ihrem Verantwortungsbereich. Selbstverständlich gewährleisten wir die einwandfreie Qualität unserer Produkte nach Maßgabe unserer allgemeinen Verkaufs- und Lieferbedingungen. Rohstoff- und fertigungsbedingt, sowie durch äußere Einflüsse (Temperatur, Luftfeuchtigkeit, etc.) können die angegebenen Werte um bis zu ± 25% schwanken.		

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INFORMATION

BSW

Produktinformation

Recoflex®, 6 mm

Überarbeitungsdatum: 20.08.2013
Druckdatum: 08.01.2015

1. Anwendungszweck	Möbelbau, Innenausbau, Messebau, Akustik		
2. Produkt	Produktname	: **Recoflex®**	
	Farbe	: holz-ähnlich	
	Material	: PUR-gebundene Matte aus Holz-, Kork- und Latexanteilen	
	Abmessung	: 6 mm	
3. Technische Daten	Raumgewicht	: 425 kg/m³	
	Flächengewicht	: 2,55 kg/m²	
	Zugfestigkeit	: 0,55 N/mm²	in Anlehnung an DIN EN ISO 1798
	Reißdehnung	: 10%	in Anlehnung an DIN EN ISO 1798
	Druckspannung bei 25 % Verformung	: 1,50 N/mm²	DIN EN ISO 3386-2
	Temperaturbeständigkeit	: - 40° C bis 115° C	
	Brandverhalten	: Klasse E	DIN EN 13501-1
4. Anmerkung	Unsere Beratung erfolgt nach bestem Wissen, gilt jedoch nur als unverbindlicher Hinweis und befreit nicht von der eigenen Prüfung der von uns gelieferten Produkte auf ihre Eignung für die beabsichtigten Verfahren und Zwecke. Die angegebenen technischen Daten sind Richtwerte, d. h. Erfahrungswerte aus längeren Produktionszeiträumen. Die Verarbeitung unserer Produkte erfolgt außerhalb unserer Kontrollmöglichkeit und liegt daher ausschließlich in Ihrem Verantwortungsbereich. Selbstverständlich gewährleisten wir die einwandfreie Qualität unserer Produkte nach Maßgabe unserer allgemeinen Verkaufs- und Lieferbedingungen. Rohstoff- und fertigungsbedingt, sowie durch äußere Einflüsse (Temperatur, Luftfeuchtigkeit, etc.) können die angegebenen Werte um bis zu ± 25% schwanken.		

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Curriculum Vitae

since 2009	PHD candidate, scientific researcher and employee at the Institute of Building Structures and Structural Design (ITKE) – University of Stuttgart
2014	First author of the pending European patent : "High-density fibreboard made of renewable raw materials, suitable for free-form modelling". Reference number: 14/001TLB
2003-2009	Scientific researcher and employee at the faculty of Engineering, Architecture Department (FEDA)-Ain Shams University, Cairo
2003-2009	Free-lancer: Architectural Engineer and Consultant, Cairo
2003 – 2006	Master of Science in Architectural Engineering (M.Sc. Eng.), Faculty of Engineering- Ain Shams University, Cairo
1998 – 2003	Bachelor of Science in Architectural Engineering (B.Sc. Eng.), Ain Shams University, Cairo. Grade: *'Distinction with Honors'*. *First Rank* in Architecture Class
2003	Honorary Prize for the graduation Project from the UIA I Egyptian National Sector
2001-2003	Award for outstanding students from the Students Union- Faculty of Engineering- Ain Shams University, Cairo (years 2003, 2002, 2001)
2001-2002	First Prize Award for the design competition of Samha Gardens, Emirates, during training at CPAS Engineer Office in Cairo (2002)
	First Prize Award for the Court-House design in Dubai, during training at CPAS Engineer Office in Cairo (2001)
1998	High School: Ramses College (ex. American College in Cairo) - *First Rank* in Math-Section. Score: *'Distinction'*
1980	Born in Cairo

Vita

Hanaa Dahy was born in Cairo in 1980. She received her Bachelor Degree in Architectural Engineering from the Ain Shams University in Cairo with a 'Distinction and Honors' score in 2003 then worked at the faculty of Engineering - Ain Shams University as a scientific researcher and lecturer.

She worked also as a free-lancer and a consultant in Cairo and worked in parallel in a number of architectural offices including 'Engineering Consultations Group, Dr. Yehia Eid' in 2004 and 'Designing and Engineering Consultations- Dr. Esam El Awadi' in 2003.

Mrs. Dahy earned her Master Degree in 'Physical Modelling Application Techniques in Architecture' in 2006 from the faculty of Engineering, Ain Shams University in Cairo. In 2009, she moved to Stuttgart in Germany, to complete her scientific researches and PHD studies.

Since 2009, Hanaa played a great role in the research and academic environment at the ITKE, especially within the scope of 'Bio-based/Green building materials and Biocomposites'. One of the developed materials accomplished in her PHD is at the moment a pending European patent, which was filed in July 2014. She also lead a number of academic courses including: 'Do It Yourself' in 2011, 'Agri-tecture' in 2013, 'Live in GREEN' in 2013/2014, in addition to her participation in the ITECH Master-Program teaching board in the faculty of Architecture at the University of Stuttgart.

She was the leader of the built research pavilion "Eco-Pavilion" in 2011, which was built from recycled materials and biocomposites together with 20 students and 15 research institutes and material companies in Germany. The pavilion and the developed materials received an international interest and was discussed in a number of international conferences, scientific meetings and magazines. Mrs. Dahy was invited by a number of renewable resources experts for speeches regarding the new methods of applying agricultural residues and natural fibres in architecture. She was also addressed by different chemical and material companies for industrial consultations within this aspect.

In December 2014, Hanaa Dahy completed her doctorate at the Institute of Building Structures and Structural Design (ITKE) at the University of Stuttgart. At the moment, she is leading a research industrial project for developing new bio-based building materials with integrated acoustic and thermal insulation properties for architectural applications, funded by the Agency for Renewable Resources (FNR), under the Federal Ministry of Food and Agriculture in Germany.