Produktion av miljöanpassade spånplattor från träavfall

Manufacturing of environmentally friendly particleboards from wood waste

Prof. Dr. Mahmood Hameed, Prof. Dr Torleif Bramryd, M.Sc Eric Rönnols
Preface

The innovation project “Manufacturing of environmentally friendly particle boards from wood waste” has been financed through funding from RE: Source and Nordvästra Skånes Renhållnings AB (NSR).

The research work was initiated and led by Dr Prof Mahmood Hameed, Academic Advisor at NSR and carried out in cooperation with Lund University, NSR Waste Treatment Dept (waste wood processing), MTA Bygg och Anläggnings AB and the Georg August University of Göttingen, Germany (mechanical and environmental tests of produced models of particle boards). Eric Rönnols, Rönnols Miljökonsult AB and Senior Advisor at NSR has served as an administrative project leader.

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<th>Project title – Swedish</th>
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<tr>
<td>Project title – English</td>
<td>Manufacturing of environmentally friendly particleboards from wood waste</td>
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<tr>
<td>Company</td>
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<td>Address</td>
<td>251 89 Helsingborg</td>
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<td>Project leaders</td>
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| Key words              | Particleboard, wood waste, albumin, tannin, environmentally friendly product, TF/PMDI, formaldehyde, rape-resin |

The project has been followed by a reference group with participation from NSR, MTA Bygg och Anläggnings AB, SYSAV Utveckling, the Municipality of Lund, the University of Lund, the University of Göttingen, KTH, Avfall Sverige (the Swedish Waste Management Association) and Pfleiderer Holzwerkstoffe GmbH as a particle board manufacturer:

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<th>Name</th>
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Definition: Wood waste comes mainly from forestry, wood industry and construction and demolition of buildings and other constructions. Three types of wood waste can be identified:

- Untreated wood waste (raw wood considered as biomass),
- Slightly treated wood waste (including glued, coated and varnished scrap wood with coatings not containing halogenated organic compounds or preservation agents) and
- Highly treated wood waste (including wood treated with CCA and creosote, and considered as hazardous waste), (Rizzo, 2010; BGBl, 2015).
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Sammanfattning

Projektidén är att skapa kommersiellt hållbara miljövänliga, innovativa modeller (varianter) av spånskivor baserade på träavfall med olika naturliga limsystem och jämföra deras mekaniska, fysikaliska och miljöegenskaper med europeiska standarder och konventionella spånskivor.


Storskalig sortering av träavfall i obehandlat träavfall, lätt behandlat träavfall, högbehandlat träavfall och trädgårdssavfall utförs av NSR på återvinningsanläggningen i Helsingborg med en mekanisk kross (CBI 640) och trumsiktar (Doppstadt 518).

Genom sortering, krossning och siktning av träavfallet med tillgänglig maskinpark har träflis, lämplig för tillverkning av spånskivor kunnat produceras från olika typer av träavfall. Kvaliteten har konstaterats bli jämförbar med flis framställ från färskt trä (flis från gran). Att använda träavfall som råvara för tillverkning av spånskivor bidrar till att öka återvinning av träavfall (ett steg upp i avfallshierarkin). Tillverkning av spånskivor från träavfall bidrar till att öka intresset för utveckling av kommersiella metoder för återvinning av träavfall hos befallingsföretag.


Innovationsprojektet har visat möjligheten att tillverka innovativa varianter av spånskivor från olika typer av träavfall (obehandlat träavfall (typ A1), lätt behandlat träavfall (AII) och trädgårdssavfall), bundna av olika gröna limsystem (hybridharts av TF och PMDI, animaliskt albumin-proteinharts och raps-harts). De fysikaliska och mekaniska egenskaperna samt formaldehydutsläpp och halten extraherbar formaldehyd hos de tillverkade modellerna uppfyllde specificationerna i europeisk standard EN 312 (2010) och uppfyllde även kraven på material för inredning (inklusive möbler) för användning vid torra förhållanden (typ P2) och/eller kravet på spånskivor för allmänna ändamål för användning vid torra förhållanden (typ P1).
Viktiga resultat från projektet är bl a:

- **dels** att vi för första gången visat på möjligheten att tillverka varianter av spånskivor från olika typer av träavfall, bundna med ett limsystem baserat på överblivna kakor från produktion av rapsolja i naturligt tillstånd,

- **dels** att de producerade varianterna uppfyllde specifikationer för europeisk standard EN 312 (2010) och kraven på typ P1 och/eller typ P2 för spånskivor och

- **dels** att varianterna kan betraktas som spånskivor med ultra-låga formaldehydutsläpp.

En förstudie beträffande extraktion av protein från kakor av rapsolja på ett enkelt sätt visar att det definitivt är en fördel att proteinet extraheras från rapskakan som en del i tillverkningen av ett ”grönt”, fossilfritt och avfallsbaserat lim.

Kontakter med möbelproducenter och designföretag visar att det finns ett stort intresse för de innovativa spånskive-varianterna som tagits fram i detta projekt. Kunder betraktar ”giftfria” material i byggande som en viktig och växande nisch. Vi bedömer att spånskivproducerande företag och limföretag inom en snar framtid kan öppna dörren för kommersiella investeringar på detta område.

I projektet har även ingått att se på strategier och metoder för separation och insamling av träavfall på byggarbetsplatser, kommersiellt, tekniskt och i relation till möjliga återvinningstillfälle. En slutsats är att det på de flesta byggarbetsplatser finns goda möjligheter att separera återvinningsträ, metall och farligt avfall från restavfall, men att det ofta rent fysiskt/logistiskt är svårt att hantera fler separata fraktioner samtidigt på arbetsplatsen. Under olika skeden av ett bygge kan det däremot vara fullt motiverat och genomförbart att vissa ytterligare fraktioner hanteras och återvinns separat, t ex schaktmassor vid grundläggning, betong/tegel vid rivning, plast, well och annat förpackningsmaterial i senare skeden av ett bygge. Att en ”restavfallsfraktion” uppstår är ofrånkomligt, även om man försöker minimera dess storlek. För denna fraktion kan återvinning ske på återvinningsanläggningar hos kommunala eller privata aktörer.

Mängden organiskt kol i träavfall som skulle kunna ackumuleras i spånskivor om dessa tillverkades av träavfall i stället för att, som idag, brännas skulle bidra med en minskning av mängden utsläptta växthusgaser motsvarande ca 0,5 miljoner ton CO₂ per år. Detta skulle kunna bidra till att minska koldioxidutsläppen från verksamheter i Sverige med nära en procent, vilket skulle medverka till att mildra växthuseffekten och det växande problemet med global uppvärmning samt att uppnå de nationella klimatmålen. Miljöpåverkan av detta alternativa utnyttjande av träavfall har beskrivits i form av livscykelanalys (LCA).

Forskningsresultaten visar att det finns möjligheter att utveckla och optimera formaldehydfria lim från rapsfröpresskaka (fossilfritt, ”grönt” lim) för produktion av spånskivor och träbaserade paneler, men att ytterligare insatser beträffande teknikutveckling och kommersialisering krävs.
Summary

The project idea is to create commercially sustainable environmentally friendly innovative models (variants) of particleboard based on wood waste using different natural adhesive systems and compare their mechanical-, physical- and environmental properties with the European Standards and conventional particleboards.

The amount of wood waste in Sweden is huge and 90% of the wood waste is used as biofuel for heat and/or production of electricity. At the same time virgin wood is the prime raw material for production of particleboards. The Swedish consumption of particleboards is today much higher than the production in Sweden. Urea formaldehyde-based adhesives are the most commonly used resins for conventional particleboard production. The formaldehyde in the boards is then as a consequence slowly emitted from products made by particleboards. Formaldehyde has cancerous effect. One of the major challenges is to produce a particleboard with low formaldehyde emissions. Alternatives to urea-formaldehyde as a binder are required.

Large-scale sorting of wood waste into untreated wood waste, slightly treated wood waste, highly treated wood waste and garden waste is performed by NSR at the recycling facility in Helsingborg, using mobile crushers/shredders (CBI 640) and drum sieves (Doppstadt 518).

Through sorting, crushing and sieving of the wood waste with available machinery wood particles (wood chips), suitable for production of particleboards has been produced. The quality of the wood chips from wood waste was comparable to wood chips produced from fresh wood (wood chips from spruce). Using wood waste as raw material for manufacturing particleboard contributes to the environmental goals regarding increased recovery of material (a step up in the waste hierarchy). The manufacturing of particleboard from wood waste contributes to raise the interest in developing commercial methods for recycling of wood waste as well as it is increasing the efficiency of wood waste recycling in several waste management companies.

In the project we have demonstrated for the first time the possibility of manufacturing three-layered particleboards based on wood waste material bonded by hybrid resin of TF and PMDI, where we succeeded in replacing PMDI as fossil binder with 40% Tannin as a natural adhesive. The produced particleboard still complies with the European Standards EN 312 (2010). An application for a worldwide patent regarding the production technology has been filed and published. International Publication Number: WO 2019/117799 A1.

The innovation project has demonstrated the possibility of manufacturing innovative variants of particle board from different types of wood waste including untreated wood waste (AI), slightly treated wood waste (AII) and garden waste, bonded with different green adhesive systems (hybrid resin of TF and PMDI, animal’s albumin-protein resin and rape seed resin). The physical- and mechanical properties as well as formaldehyde release and content of extractable formaldehyde
of the manufactured models complied with the specifications of European standard EN 312 (2010) and fulfilled the requirement for interior fitments (including furniture) for use in dry conditions (Type P2) and/or the requirement for particle boards for general purposes for use in dry conditions (Type P1).

Major conclusions from the tests with “green” adhesives are:

- It has been demonstrated for the first time the possibility of manufacturing innovative variants of particle board from different types of wood waste, bonded by an adhesive system based on leftover cakes of rape oil in natural state.

- The quality of the produced particleboards complied with the specifications of European standard EN 312 (2010) and fulfilled the requirement for particle board type P1 and/or type P2,

- The produced variants can be considered as particleboards with ultra-low formaldehyde emission.

The results from a preliminary test to extract protein from left over cakes of rape oil in a simple way reveal that it is definitely an advantage to extract protein from the left over cake of rape oil to create a “green”, fossil free adhesive based on a waste product.

Contacts with furniture producing- and design companies shows a great interest in the innovative particle boards variants in the project. Customers sees non-toxic materials in buildings as an important and niche. We can see that in the near future particle board-producing companies as well as adhesive companies will open the door for commercial investments in this field.

Within the project one part has been to look at strategies and methods for separation and collection of wood waste at construction sites, from a commercial, technical and recycling point of view.

A conclusion is that at most construction sites there are favorable conditions for separation of recyclable wood, metals and hazardous waste from residual waste. On the other hand, it is normally difficult physically and logistically to handle more fractions separately, due to lack of space. During different phases of a project also other fractions could and should be handled separately, for example clean and/or contaminated soils from excavations, concrete/bricks during demolition, plastic, cardboard and other packaging materials at the final stage of the construction. But it is most likely always impossible to avoid a fraction also with residual/mixed waste, even though you try to minimize it. This fraction can be sorted and to some extent recycled together with other types of industrial waste at municipal or private waste management sites.

The amount of organic carbon that could be accumulated in particleboards if these were manufactured from wood waste, as an alternative to incineration of the wood waste, could result in a decrease of greenhouse gases equivalent to 0,5 million tons of CO₂/year. This would contribute to decrease the carbon dioxide emission from activities in Sweden with nearly one percent, thereby contributing to mitigate the
greenhouse effect and the growing problem of global warming as well as to the achievement of the national climate goals. The environmental impact of this alternative utilization of wood waste has been described in the form of life cycle analysis (LCA).

The research results demonstrate a possibility to develop and optimize formaldehyde-free adhesives from rapeseed press cake (green adhesive) to produce particleboards and wood-based panels. Further research is needed and recommended to develop and commercialize the technology.
**Introduction and background**

Manufacturing of particleboards from wood waste contributes to accumulation of organic carbon and thus to mitigation of greenhouse effect. Burning of wood waste to produce heat and/or electricity on the contrary adds to a quick release of carbon dioxide to the atmosphere and adds to the growing problem of global warming (Mansour and Hameed, 2013).

The amount of wood waste in Sweden is huge, about 1,7 million tons (SCB, 2016), which is equivalent to approx. 5,7 million m$^3$ of wood chips with a density of 290 kg/ton (Avfall Sverige 2000). 85 - 90 % of the wood waste is used as biofuel for heat and/or production of electricity, see Table 1 below.

At NSR, serving a region with 262 000 inhabitants, the yearly amount of wood waste reaching the recycling plant in Helsingborg exceeds 20 000 tons, including some 5 000 tons of clean, unpainted wood (pallets, etc.).

**Table 1** Treatment of wood waste (non-hazardous waste) in Sweden, 2010, 2012, 2014 and 2016, tons/year

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<tr>
<td>Recovery as material</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>870</td>
</tr>
<tr>
<td>Composting and anaerobic digestion</td>
<td>65 700</td>
<td>49 900</td>
<td>25 600</td>
<td>20 000</td>
</tr>
<tr>
<td>Backfilling</td>
<td>1 360</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Reuse, including capping of landfills</td>
<td>26 300</td>
<td>8 350</td>
<td>4 390</td>
<td>1 380</td>
</tr>
<tr>
<td>Use as biofuel</td>
<td>1 320 000</td>
<td>1 144 000</td>
<td>1 556 000</td>
<td>1 955 000</td>
</tr>
<tr>
<td>Landfilling</td>
<td>60</td>
<td>6 460</td>
<td>4 390</td>
<td>0</td>
</tr>
<tr>
<td>Pretreatment and sorting</td>
<td>480</td>
<td>12 300</td>
<td>128 000</td>
<td>301 000</td>
</tr>
<tr>
<td><strong>Total, treated non hazardous wood waste</strong></td>
<td><strong>1 413 900</strong></td>
<td><strong>1 221 010</strong></td>
<td><strong>1 718 380</strong></td>
<td><strong>2 318 250</strong></td>
</tr>
</tbody>
</table>

Source: SCB, Officiell statistik, statistikdatabasen, 2019

Sweden’s consumption of particleboard (954 000 m$^3$) is more than the production in Sweden, 494 000 m$^3$ according to FAO statistics, 2014. Therefore, it is very interesting to investigate how we can sort and use wood waste as a resource to manufacture particleboard. It is also interesting to characterize the formaldehyde release from particleboard based on wood waste and bonded by different adhesives like tannin formaldehyde (TF-resin: natural binders) and polymers based on Diphenylmethane-diisocyanate (PMDI), which bind wood without adding any formaldehyde scavenger or catalysts (urea, melamine, resorcinol).

Urea formaldehyde (UF) based adhesives are the most commonly used resins for conventional particleboard production in Europe and USA. To decrease the formaldehyde release addition of a formaldehyde scavenger and catalysts is required for reaching the E1 (<6,5 mg/100g) or lower emission classes. Environmentally friendly products are becoming more widely used. These products are nontoxic and are made from renewable or recyclable resources (Spiegel and Meadows, 1999; Hameed, 2015; Hameed et. al., 2005). Particleboard is one of the common materials used in building constructions. It serves numerous functions as cabinetry, table tops, shelving wall and floor panels, doors and furniture (Deppe and
Ernst, 1992; Hygreen et. al., 2003; Paulitsch and Barbu, 2015). One of the major challenges is to produce boards with low formaldehyde emissions and at the same time decrease the input of binders with a fossil origin.

Formaldehyde is a volatile organic compound (VOC) released from particle board into the air. Exposure to formaldehyde in concentration greater than 0.1 part per million (ppm) can cause nasal and throat congestion, burning eyes, headaches as well as cancer (Roffael, 1993; ECA, 2000; Gelbke, 2008). Alternatives to urea-formaldehyde as a binder are required to reduce and eliminate the formaldehyde emission into the air.

Some research related to this topic has focused on the manufacturing of particleboard from agricultural waste; Hameed (2007, 2008) published work related to the possibility of manufacturing urea- formaldehyde bonded particleboard as well as medium density fiberboard from cotton stems. Mosseily and Hameed (2012) tried the alternative strategy of producing particleboard by using urea formaldehyde resin and a by-product of the olive production.


Comparatively, only a few publications related to the possibility of manufacturing tannin formaldehyde or PMDI bonded particleboard based on waste wood material have been printed (Rosamah, 2003; Bisanda et. al., 2003; Zwang et. al., 2004; Moa et. al., 2011; Noman et. al., 2014; Pizzi, and Walton, 1992; Pizzi et al. 1995, Tondi and Pizzi, 2009). Efforts have been made to mix PMDI with other adhesives, such as urea formaldehyde adhesive (UF), melamine formaldehyde adhesive, and phenol formaldehyde adhesive (PF); [Deppe 1977; Tinkelenberg et al. 1982; Pizzi and Walton 1992; Hao and Liu 1993a, 1993b; Pizzi et al. 1995; Grigoriou 2000; Frick and Motter 2001; Simon et al. 2002).

However, manufacturing particleboards from wood waste, bonded by a combination of tannin formaldehyde resin (TF-resin) and polymeric diphenylmethane-diisocyanate (PMDI) as an adhesive system also seems to be
possible, which has been demonstrated through our pre-study “(RE:Source Project 42507-1)” (Hameed et al., 2017).

We find it is important as one of the objectives of this project to investigate the feasibility of manufacturing models of particleboard based on wood waste and bonded by hybrid resin of TF and PMDI to clarify to what extent the replacement of PMDI as a fossil binder by tannin resin as a natural binder is possible and furthermore to investigate the feasibility of manufacturing fossil-free models of albumin-protein bonded particleboard (renewable adhesive from botanical sources or even animal’s sources).

It was observed through research conducted in Germany that the fresh wood chips of pine and spruce has a weak ability to bind with adhesives as urea formaldehyde, because of its high content of wood extractives (resin and fatty acids), while stored wood chips of pine or spruce showed a great ability to bind with adhesives as urea formaldehyde by particleboard manufacturing. This was attributed to the disintegration of wood extractives (resin and fatty acids) during the storage process (Roffael and Dix, 1994) and thus were some mechanical- and physical specifications better for particleboard manufactured from stored wood chips of pine and spruce than particleboards manufactured from fresh wood chips of pine and spruce (Schäfer, 1996).

Wood chips from clean unpainted wood waste may have a similar behavior as stored wood chips, so it is important from environmental point of view to investigate the possibility of manufacturing models of particleboard from wood chips obtained from clean wood waste and comparing them with models of particleboard manufactured from fresh wood chips from softwood trees (pine or spruce).

**Project objectives**

The main objective of this project is to create commercially sustainable environmentally friendly models of particleboards, based on different wood waste types and different natural adhesive systems and test the compliance with the European Standards, regarding both physical- and mechanical properties and the formaldehyde release.

**Other objectives**

1- Investigate the feasibility of manufacturing innovative, environmentally friendly models of particleboards bonded with different adhesive systems (hybrid resin of TF and PMDI, UF and renewable adhesive from botanical and animal sources), including to what extent the replacement of PMDI as a fossil binder by tannin resin as a natural binder is possible.

2- Investigate the feasibility of manufacturing new models of particleboard from wood waste with low and ultra-low formaldehyde emission.

3- Estimate the positive environmental effect of recycling of wood waste for manufacturing of particleboards instead of burning it just to recover the energy,
including calculations of accumulated organic carbon “captured carbon” and
decrease of emissions of greenhouse gases, describing this in the form of life
cycle analysis (LCA).

4- Investigate the differences between models of particleboard manufactured
from wood chips obtained from untreated wood waste made of massive wood
(type AI) and models of particleboards manufactured from fresh wood chips
obtained from softwood trees (spruce).

5- Develop appropriate methods for recycling of wood waste at construction
sites.

6- Investigate appropriate methods for sorting and pretreatment of wood waste for
recycling at waste management sites.

**Project Implementation**

The project work has been implemented from July 2017 up until June 2019 and
has included the following tasks:

1- Collection of data about production of particleboards in Sweden/
Scandinavia/Europe and the use of wood waste in the production
Responsible: University of Lund (prof Torleif Bramryd).

2- Preparation and characterization of wood particles from different kinds of
wood waste at NSR, Helsingborg, as raw materials for manufacturing
various models of particleboard. Responsible: NSR (prof Mahmood
Hameed).

Separation of wood chips from different types of sorted wood waste
(untreated wood waste, slightly treated wood waste and garden waste) was
performed by NSR waste management personnel at the recycling site in
Helsingborg. The machinery used was a wheel-loader (Volvo), a CBI
Magnum Force 6400 crusher equipped with magnetic separator and a
Doppstadt SM-518 drum sift equipped with rotary mesh sieve 10 mm,
which was selected to minimize the amount of gravel and impurities.

Preparation of the wood chips from the sorted wood waste was done by
NSR. The wood chips for each type of the sorted wood waste that passed
through the sieve was characterized.

3- Manufacturing 15 models of particleboards at Georg August Universität,
Göttingen. Responsible: Göttingen University and NSR NSR (prof Alireza
Kharazipour, Göttingen and prof Mahmood Hameed, NSR).

- Determination of the physical and mechanical properties of the
manufactured models of particleboards, according to European
Norms EN (2010). Responsible: Göttingen University and NSR
(prof Alireza Kharazipour and prof Mahmood Hameed)
- Determination of the formaldehyde release from the manufactured models of particleboards. Responsible: Göttingen University and NSR (prof Alireza Kharazipour and prof Mahmood Hameed)

Approximately 350 kg wood chips from NSR and 25 kg sawdust from a MTA construction site was transported to Georg August University of Göttingen in Germany where the material was analyzed and processed in the Büsgen-Institute.

The wood chips and the sawdust were used as raw material to manufacture 15 different models (variants) of particleboards (three replicates of each variant) using different adhesives systems. The physical and mechanical properties as well as the formaldehyde release of the manufactured models were determined according to European standards. The laboratory work was conducted by the research team led by prof Alireza Kharazipour, together with prof Mahmood Hameed. A technical report written by Prof. Dr. Alireza Kharazipour summarizes the results.

4- Determine the amount of long term accumulated organic carbon from manufacturing particleboard from wood waste in Sweden/Scandinavia/Europe. Responsible: Lund University (prof Torleif Bramryd).

5- Statistical analysis of data. Describing the environmental impact of alternative utilization of wood waste in the form of life cycle analysis (LCA), as well as calculating reduced carbon dioxide emissions due to the recycling of wood waste. Responsible: Lund University (prof Torleif Bramryd)

6- Separation of wood waste at construction sites. Pilot study at existing sites. Assessment of possibilities and constrains. Responsible: NSR and MTA (Henrik Gullberg and Ulrika Lejdström, MTA, Eric Rönnols, Rönnols Miljökonsult and Lotta Lewis-Jonsson, NSR).

In cooperation with MTA Bygg och Anläggning AB methods, possibilities and constraints for separation of wood waste at smaller construction sites was studied and compared with economical and technical effects of sorting the mixed waste at the waste management site.

7- A preliminary investigation on simplified extraction of protein from left over cakes from rape oil production Responsible: NSR (prof Mahmood Hameed)

8- Commercial opportunities, Contacts with particleboard producers and furniture producing- and design companies to explore the interest in the innovative particleboards variants produced in the project. Responsible: NSR (prof Mahmood Hameed).

In which “niches” the use of the environmentally friendly particle board can be particularly interesting has been discussed in contact with particle board-producing companies, designers, furniture manufacturers, adhesive companies interested in the new adhesive systems and rapeseed press cake-
producing companies. The contacts open the door for commercial investment in coming stages. Furniture producing- and design companies as well as customers consider that a niche for non-toxic particle boards variants, in line with the results from this project, certainly exists, for example in hospitals, schools, kindergarten, offices, etc. The ultra-low formaldehyde release and formaldehyde-free particleboards seem to be completely in line with their wishes.

9- Conclusions, final report, summarizing the project. Responsible: NSR and Lund University (prof Marmood Hameed, Eric Rönnols, prof Torleif Bramryd).

10- Presentation of the project externally. Responsible: NSR (prof Mahmood Hameed, Eric Rönnols),

11- Publishing of scientific articles regarding results from the project. Responsible: NSR (prof Mahmood Hameed).

The results of the trials carried out in the project were published in scientific journals for the wood industry (eg, the German Holtztechnologie) and in magazines with the waste industry as target group (eg, Avfall Sverige monthly magazine “Avfall och Miljö”).

Results and Discussion

Data Collection

Construction and demolition waste in Sweden

During building activities, a total of approximately 9.8 million tonnes of construction and demolition waste was produced in Sweden in 2016, of which just under 0.4 million tonnes was hazardous waste. This corresponds to 31 per cent of all generated waste in Sweden (mining waste was excluded) and 16 percent of all hazardous waste. Approximately 50 percent of the sector's waste was recycled in 2016, as well as in 2012 and 2014. However, large flows of construction and demolition waste are not included in the waste statistics, especially products where recycling can be done momentarily, like concrete and asphalt (Boverket 2019).

If Sweden is to achieve the national environmental quality objectives "Good built environment" and "Non-toxic environment", the amount and toxicity of construction and demolition waste must be reduced, and the management ensured through e.g. recycling. The construction companies are responsible for the management of waste from construction and demolition, but the National Board of Housing, Building and Planning is also engaged in works aiming at reducing the quantities and the toxicity of the demolition waste produced (Boverket 2017).

Post-consumer wood waste should not be thought of as waste but rather as a useful resource/raw material for new products. The amount of wood waste
increased clearly in 2016, but this waste is mainly combusted for energy recovery and does not contribute to the recycling target.

Within the national environmental target system, there are 24 interim targets aiming at facilitate the opportunities to reach the “generation goal” and the environmental quality norms. One of the milestones is called “Increased resource management in the construction sector” and has the following goal:

Efforts shall be made so that re-use and recycling of material from non-hazardous building and demolition waste is at least 70% by weight by 2020.

Wood recycling as a material resource is an important factor to achieve this. The amount of wood waste in Sweden 2016 was about 2 million tons (SCB, 2019), which is equivalent to approx. 5.7 million m$^3$ of wood chips with a density of 290 kg/m$^3$. 85 - 90 % of the wood waste is used as biofuel for heat and/or production of electricity, and almost nothing as a resource for producing new building material (WBPI 2015).

**International overview**

The total amount of particle board produced in the World is around 220 million m$^3$/year. This corresponds to about 30-35 million tons of organic carbon, or about 90 million tons of CO$_2$.

Only a small proportion of the raw material is wood waste. However wood waste is used as raw material in some countries, predominately in western Europe, especially if the domestic forest resources are sparse. It is also more common in countries with established wood recycling sectors and relevant consumer base. The country in the EU relative use of wood waste in board production is Italy (95 %), followed by Belgium (70 %) and Denmark (67 %) (Fel! Hittar inte referenskälla.). Also Germany uses a large amount of wood waste for board production, even if the percentage is lower (30 %).

The use of waste wood for board production in Sweden is more or less negligible (WBPI 2015). Belgium and Italy import a large amount of wood waste from France to be used as raw material for board production (Table 2). France has become the key supplier of wood waste for panel production in these neighbouring countries, while domestically the share of wood waste used in the raw material mix still remains low. Most of this exported wood waste originates in eastern France, with the northeast supplying predominantly to Belgium and in the southeast to Italy. Belgium also imports wood waste from the UK and the Netherlands., and Italy imports from e.g. Switzerland. (WBPI 2015). The prizes on raw material for panel and board production has increased due to competition with the energy sector, using wood waste as a fuel. Thus also much of the transportation between countries in Europe concerns waste wood as raw material for energy production. Especially countries with a high rate of waste incinerators with over-capacity, like Sweden, Germany, Holland and Belgium import large amounts of wood waste to be used as
fuel. This can be a problem for implementing a higher rate of material recycling of wood.

However, there are also examples, e.g. in Belgium, where sustainability and green marketing are the driving forces for using waste wood as a raw material for board production, and thus as a material resource with higher priority in the waste hierarchy (WBPI 2015). In Sweden waste wood is mostly used as a fuel, while more modest amounts are used for e.g. composting, substrate on pedestrian paths and for landfill cover (table 2). Due to increasing interest for implementing a circular economy, and due to increased concern about carbon dioxide balances some waste companies have started to separate wood waste for recycling, but this is mainly exported e.g. to Poland.

Table 2. Wood waste consumption in particleboard production, Europe, 2015 (WBPI, Wood Based Panel International, 2015)

<table>
<thead>
<tr>
<th>Country</th>
<th>Particleboard production 2013, '000m²</th>
<th>Share of wood waste in raw material mix</th>
<th>National consumption of wood waste in panels, '000 tonnes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>5,600</td>
<td>30%</td>
<td>1,400</td>
</tr>
<tr>
<td>France</td>
<td>3,811</td>
<td>22%</td>
<td>680</td>
</tr>
<tr>
<td>Italy</td>
<td>2,652</td>
<td>95%</td>
<td>2,150</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>2,012</td>
<td>52%</td>
<td>890</td>
</tr>
<tr>
<td>Austria</td>
<td>1,840</td>
<td>35%</td>
<td>550</td>
</tr>
<tr>
<td>Spain</td>
<td>1,465</td>
<td>32%</td>
<td>390</td>
</tr>
<tr>
<td>Belgium</td>
<td>1,250</td>
<td>70%</td>
<td>850</td>
</tr>
<tr>
<td>Sweden</td>
<td>600</td>
<td>0%</td>
<td>-</td>
</tr>
<tr>
<td>Portugal</td>
<td>590</td>
<td>25%</td>
<td>130</td>
</tr>
<tr>
<td>Switzerland</td>
<td>370</td>
<td>0%</td>
<td>-</td>
</tr>
<tr>
<td>Denmark</td>
<td>316</td>
<td>67%</td>
<td>180</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Treatment method</th>
<th>2010</th>
<th>2012</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composting and anaerobic digestion</td>
<td>65 700</td>
<td>49 900</td>
<td>25 600</td>
</tr>
<tr>
<td>Backfilling</td>
<td>1 360</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Reuse, including capping of landfills</td>
<td>26 300</td>
<td>8 350</td>
<td>4 390</td>
</tr>
<tr>
<td>Use as biofuel</td>
<td>1320 000</td>
<td>1144 000</td>
<td>1556000</td>
</tr>
<tr>
<td>Landfilling</td>
<td>60</td>
<td>6 460</td>
<td>4 390</td>
</tr>
<tr>
<td>Pretreatment and sorting</td>
<td>480</td>
<td>12 300</td>
<td>128 000</td>
</tr>
<tr>
<td><strong>Total, treated non-hazardous wood waste</strong></td>
<td><strong>1413 900</strong></td>
<td><strong>1221 010</strong></td>
<td><strong>1718380</strong></td>
</tr>
</tbody>
</table>
Figure 1. Wood waste trade flows for panel production, WBPI, 2015

Sorting and pretreatment of wood waste

Characterizing of wood wastes at NSR Company

The annual quantity of wood waste received at NSR recycling plant in Helsingborg is around 30 000 tons. The wood waste includes discarded furniture, packaging material, pallets made of massive wood or wood-based panels, particleboard, fiberboard and other wood based building and construction residues (Figure 2). In addition to this also 15 000 - 20 000 tons of garden waste, residues from silviculture treatment and tree trimmings are received at the facility (Figure 3).
Large-scale sorting and pre-processing of wood waste at NSR facility

At the site incoming wood waste is handled according to the quality and could be divided into the following three types (Rizzo, 2010; BGBl, 2015):

1. Untreated (Clean, unpainted wood waste) wood waste made of massive wood (AI), Figure 4.
2. Slightly treated wood waste (issued from glued, coated and varnished scrap wood with coatings not containing halogenated organic compounds or preservation agents) made of massive wood or particleboards, medium density fiberboard, OSB, plywood or others wood-based panels (AII). Figure 5.
3. Highly treated wood waste (issued from impregnation treatments with wood preservatives (chromate copper arsenate (CCA) and creosote), and considered as hazardous wastes) (AIII, AIV). Figure 6.
4. Garden waste, residues from silviculture treatment and tree trimmings. Figure (7).

**Figure 4.** Untreated (Clean, unpainted wood waste) wood waste made of massive wood (A1).

**Figure 5.** Slightly treated wood waste (issued from coating or gluing treatments) made of massive wood or wood-based panels (AII).
Figure 6. Highly treated wood wastes (issued from impregnation treatments with wood preservatives (chromate copper arsenate (CCA) and creosote), and considered as hazardous wastes) (AIII, AIV).

Figure 7. Garden waste, residues from silviculture treatment and tree trimmings.
Preparation and characterizing of wood particles for manufacturing of particleboards

For producing wood chips as raw material for manufacturing the models of particleboard in this project sorted wood wastes Al, AII and Garden waste around 12 m³, 15 m³ and 10 m³ respectively were crushed separately four times by using crusher CBI Magnum Force 6400/OHLSSONS equipped with magnetic band (Figure 8). The produced wood particles from the sorted wood wastes Al, AII and Garden waste are illustrated in Figure 9 and the separated metals; nails, screws etc. in Figure 10.

The produced wood particles were screened (sifted) separately using a drum-sift, Doppstadt SM-518 PROFI, (Figure 11), equipped with rotary mesh sieve 10 mm (“the smallest available mesh size”). The wood particles retained on the sieve (Fraction I) consists of oversize wood particles, that must be re-crushed, and the wood particles that passed through it termed as Fraction II, and this fraction is used to manufacture our models of particleboard in this project.

Around 1 m³ sample of wood particles was taken from fraction II for each type of the sorted wood waste “Al, AII and Garden waste” and placed in large bags (Figure 12). The produced wood particles were characterized by taking three randomize 1 kg samples from each bag and tagged: Al1, Al2, Al3 and AII1, AII2, AII3 and GW1, GW2, GW3(Figure 13). The composition of the samples was described and the percentage of gravel and impurities was calculated (Table 4). It can be seen from Table 4, that the amount of gravel and impurities [0.61%] had decreased significantly compared with the result reported in the pilot project (RE:source no. 42507-1) [4.83%] due to more efficient sorting of the wood waste and a different choice of mesh sieve. Also mixing with gravel and stones on the sorting site during the loading process to feed the machines with the wood material was avoided.

Thus we can conclude that, the efficiency of NSR equipment used in large-scale sorting of wood waste was improved and can provide wood particles quite suitable for manufacturing of particleboard, which is important in a waste recycling perspective.
Figure 8. The crusher CBI Magnum Force 6400/OHLSSONS.

Figure 9. The produced wood particles from the sorted wood wastes AI, AII and Garden waste (GW) after four times crushing.
Figure 10. The separated metals; nails, screws.

Figure 11. Drum-sift, Doppstadt SM-518 PROFI.
Figure 12. A big sample of wood particles was taken from fraction II for each type of the sorted wood wastes “AI, AII and Garden waste”

Figure 13. Three randomize samples from each bag.
Table 4. Characterization of wood particles produced from the sorted wood wastes “AI, AII and Garden waste (GW)”.

<table>
<thead>
<tr>
<th>Wood waste type</th>
<th>Amount of gravel and impurities in the current study (%)</th>
<th>Amount of gravel and impurities in the Pilot-project (%)</th>
<th>Description of the components</th>
</tr>
</thead>
<tbody>
<tr>
<td>AI</td>
<td>0.58</td>
<td>4.83</td>
<td>Particles of massive wood</td>
</tr>
<tr>
<td>AII</td>
<td>0.65</td>
<td></td>
<td>Particles of massive wood and wood-based panels</td>
</tr>
<tr>
<td>GW</td>
<td>0.61</td>
<td></td>
<td>Particles of massive wood, bark, leaves and roots</td>
</tr>
<tr>
<td>Total (%)</td>
<td>0.61</td>
<td>4.83</td>
<td></td>
</tr>
</tbody>
</table>

Manufacturing and testing 15 models of particleboard

Materials and methods

Raw Materials

A sample of wood particles was taken from fraction II for each type of the sorted wood wastes “AI, AII and Garden waste” at NSR AB (North West Scania Recycling Company) in Helsingborg, in Sweden 140 kg, 150 kg and 20 kg respectively, in addition to 25 kg sawdust from the construction site (MTA-company). The samples were placed in 4 large bags (Figure 14), that were then transported to the University of Göttingen (Germany) where they were analyzed in the Büsgen-Institute, Department of forest botanic and tree physiology and used as raw material to manufacture 15 different variants of particle board (Three replicates for each of them) (Table 5) using the following adhesives systems:

a. A new adhesive system combining Tannin Formaldehyde resin (TF) and Polymeric Diphenylmethane-diisocyanate (PMDI)TF-PMDI hybrid resin.

b. A conventional adhesive system (Pfleiderer adhesive system Urea Formaldehyde (UF 350).

c. An albumin-protein adhesive (renewable adhesive from animal’s blood).

d. An albumin-protein adhesive (renewable adhesive from botanical sources based on a leftover cakes of rape oil in natural state).

General Information about the used adhesive systems are listed in Table 6.
Figure 14. Samples of wood particles (fraction II) from the different types of the sorted wood wastes “AI, AII and Garden waste” at NSR as well sawdust from a construction site (MTA Bygg och Anlägning AB).
Table 5. 15 variants of particle board from different wood waste types bonded with different adhesives systems

<table>
<thead>
<tr>
<th>Variant’s name</th>
<th>Variant’s number</th>
<th>The raw materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>One layer a combination of TF-resin, PMDI hybrid resin: 30:70% bonded particle board</td>
<td>V1</td>
<td>Mixture of chips obtained by mechanical disintegration of discarded furniture, packaging and pallets made of massive wood, particleboards, or others wood-based panels. All</td>
</tr>
<tr>
<td>One layer a combination of TF-resin, PMDI hybrid resin: 40:60% -bonded particle board</td>
<td>V2</td>
<td>Mixture of chips obtained by mechanical disintegration of discarded furniture, packaging and pallets made of massive wood, particleboards, or others wood-based panels. All</td>
</tr>
<tr>
<td>Three layers UF-bonded particleboard. (Adhesive system by Pfleiderer)</td>
<td>V3</td>
<td>Mixture of chips obtained by mechanical disintegration of discarded furniture, packaging and pallets made of massive wood, particleboards, or others wood-based panels. All</td>
</tr>
<tr>
<td>Three layers UF-bonded particleboard. (Adhesive system by Pfleiderer)</td>
<td>V4</td>
<td>Chips obtained from clean unpainted wood wastes (discarded furniture, packaging and pallets made of massive wood). AII</td>
</tr>
<tr>
<td>Three layers UF-bonded particleboard. (Adhesive system by Pfleiderer)</td>
<td>V5</td>
<td>Wood chips obtained from discarded furniture, packaging and pallets made of massive wood (SL) and chips obtained by mechanical disintegration of discarded furniture, packaging and pallets made of particleboards or other wood-based panels (CL). AI+All</td>
</tr>
<tr>
<td>Three layers UF-bonded particleboard. (Adhesive system by Pfleiderer)</td>
<td>V6</td>
<td>Fresh wood chips obtained from softwood trees (spruce).</td>
</tr>
<tr>
<td>Three layers albumin-protein bonded particleboard (renewable adhesive from animal’s blood).</td>
<td>V7</td>
<td>Chips obtained from clean unpainted wood wastes (discarded furniture, packaging and pallets made of massive wood). AII</td>
</tr>
<tr>
<td>One layer albumin-protein-bonded particleboard (renewable adhesive from animal’s blood).</td>
<td>V8</td>
<td>Mixture of chips obtained by mechanical disintegration of discarded furniture, packaging and pallets made of massive wood, particleboards, or others wood-based panels. All</td>
</tr>
<tr>
<td>Three layers a combination of TF-resin, PMDI hybrid resin: 40:60%-bonded particle board</td>
<td>V9 (Innovative)</td>
<td>Fresh wood chips obtained from softwood trees (spruce).</td>
</tr>
<tr>
<td>Three layers a combination of TF-resin, PMDI hybrid resin:30:70%-bonded particle board</td>
<td>V10 (Innovative)</td>
<td>Chips obtained from clean unpainted wood wastes (discarded furniture, packaging and pallets made of massive wood). AII</td>
</tr>
<tr>
<td>Three layers a combination of TF-resin, PMDI hybrid resin: 40:60%-bonded particle board</td>
<td>V11 (Innovative)</td>
<td>Chips obtained from clean unpainted wood wastes (discarded furniture, packaging and pallets made of massive wood). AII</td>
</tr>
<tr>
<td>Three layers of Rape-bonded particle board: 6%:5% (renewable adhesive from leftover cake of rape oil).</td>
<td>V12 (Innovative)</td>
<td>Chips obtained from clean unpainted wood wastes (discarded furniture, packaging and pallets made of massive wood). AII</td>
</tr>
<tr>
<td>Three layers of Rape-bonded particle board: 6%:5% (renewable adhesive from leftover cake of rape oil).</td>
<td>V13 (Innovative)</td>
<td>Wood chips obtained by mechanical disintegration of discarded furniture, packaging and pallets made of particleboards or other wood-based panels. All</td>
</tr>
<tr>
<td>Three layers of Rape-bonded particle board: 6%:5% (renewable adhesive from leftover cake of rape oil).</td>
<td>V14 (Innovative)</td>
<td>Wood chips obtained from discarded furniture, packaging and pallets made of massive wood (SL) and chips obtained by mechanical disintegration of discarded furniture, packaging and pallets made of particleboards or other wood-based panels (CL). AI+All</td>
</tr>
<tr>
<td>Three layers of Rape-bonded particle board: 6%:5% (renewable adhesive from leftover cake of rape oil).</td>
<td>V15 (Innovative)</td>
<td>Wood chips obtained from wood residues of Silviculture treatment and tree trimmings. (Garden waste GW) (CL) and saw dust from the Construction site SD (SL).</td>
</tr>
</tbody>
</table>
Table 6. Information about the used adhesives: PMDI, TF-resin, TF resin and PMDI, Animal’s albumin-protein resin and Rape resin

<table>
<thead>
<tr>
<th>Adhesives</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMDI</td>
<td>EM 4352 from HUNTSMAN</td>
</tr>
<tr>
<td>TF resin</td>
<td>Quebracho tannin from Industria Argentina Unitan S.A.I.C.A company (GT 5) powder. TF prepared according to NSR secret recipe, which is being patented</td>
</tr>
<tr>
<td>TF resin and PMDI</td>
<td>Quebracho tannin powder, EM 4352 (combination 30:70%; 40:60%) TF prepared according to NSR secret recipe, which is being patented</td>
</tr>
<tr>
<td>UF resin</td>
<td>Kaurit 350 BASF</td>
</tr>
<tr>
<td>Animal’s albumin-protein resin</td>
<td>Modified protein, Fritz Häcker GmbH + Co. KG</td>
</tr>
<tr>
<td>Rape-resin “Botanical’s albumin-protein resin”</td>
<td>By product of Rape oil (left over cakes) NSR secret recipe</td>
</tr>
</tbody>
</table>

**Preparation of Particles**

The samples of wood particles produced from each type of the sorted wood wastes “AI, AII and Garden waste” as well sawdust were chipped by using a knife ring flaker; Moduls System ø 60 cm (Figure 15). The moisture content of the produced wood particles was 13.8% (four replicates by using Sartorius MA). The produced particles were screened using a Tumbler-sift machine; ALLGAIER (Figure 16), equipped with changeable sieves with different meshes 4 mm x 4 mm and 3.15 mm x 1 mm (CL), 3 mm x 1 mm and 0.4 mm x 0.4 mm (SL). The wood particles retained on 4 mm -mesh sieve were re-chipped. The wood particles passed through 4 mm-mesh sieve and retained on 3.15 mm-mesh sieve were used for core layer [Figure 17]. The wood particles passed through 3mm-mesh sieve and retained on 0.4mm-mesh sieve were used for surface layers (15 kg, 12.3% MC) [Figure 18]. The wood particles passed through 0.4mm-mesh sieve should be removed (Fines and wood dust). The wood particles fractions of the core layer as well as surface layers were characterized by using a Laboratory screen analysis system; Retsch AS 400 (250 rpm for 5 min) and listed in Table 7.
Figure 15. A knife ring flaker; Moduls System ø 60 cm.

Figure 16. A Laboratory Tumbler-sift machine; ALLGAIER.

Figure 17. Wood fraction for core layer.
Figure 18. Wood fraction for surface layers.

<table>
<thead>
<tr>
<th>Core layer</th>
<th>Surface layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraction (Sieve mesh size)</td>
<td>Mass-%</td>
</tr>
<tr>
<td>&gt;4mm</td>
<td>1.5</td>
</tr>
<tr>
<td>&gt;3.15mm and ≤4mm</td>
<td>11.0</td>
</tr>
<tr>
<td>&gt;1mm and ≤ 3.15mm</td>
<td>83.5</td>
</tr>
<tr>
<td>≤ 1.0mm</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 7. Screen analysis of the wood particles used in the core layer and the surface layers.

Board manufacturing
15 variants of medium density particleboards were fabricated by using different adhesives (UF-resin, a combination of TF: PMDI, Animal’s albumin-protein resin and Rape-resin). Wood particles of SL and CL were oven dried at 75°C using a drying cabinet to reach about (approximately) 2% moisture content (Figure 19). Constant weight of particles was weighted to obtain the targeted final bulk density of 0.64 g/cm³ and thickness of 19 cm. The wood particles were mixed (blended) with different adhesives (UF-resin, a combination of TF: PMDI, Animal’s albumin-protein resin and Rape-resin) using a Laboratory-type blender (Figure 20). Immediately, the mixed particles were hand-felted into a frame 70 x 46 cm on metal plate and pre-pressed by hand. Thereafter, the frame was removed (Figure 21) and the mat was hot pressed by 200°C using a laboratory press, model Siempelkamp (Figure 22). The pressed particleboard was then trimmed (700 mm x 450 mm) to avoid edge effects (Figure 23) and sanded (grain size 60) to a board thickness of 18 mm by using a wide belt sanding machine (Type FW 950 C/Co. Felder KG, Hall in Tirol/Austria) (Figure 24). The boards were then conditioned for 1 week at 65±5% relative humidity and 20°C to reach equilibrium moisture content, cut into various sizes for testing according to the used standards. The production parameters of the
15 variants of particleboard are listed in Table 8. The manufactured variants are categorized according to the adhesive system used into the following groups:

1. **Group I.** Variants of one layer a combination of TF-resin, PMDI hybrid resin: 30:70% and 40:60% -bonded particle board from wood waste AII. (V1 and V2). (TF-resin was prepared according to recipe of Göttingen University preliminary variants. (3% resin). Figure 25

2. **Group II.** Variants of three layer of UF-resin bonded particle board from wood waste AI, AII, AI+AI and from fresh wood as a conventional adhesive system fossil origin. (V3, V4, V5, V6). Figure 26

3. **Group III.** Variants of three layer Albumin-protein -bonded particle board from wood waste AI (V7) and one layer Albumin-protein -bonded particle board from wood waste AII (**Innovative variants: V7, and V8**). Figure 27

4. **Group IV.** Variants of three layer a combination of TF-resin, PMDI hybrid resin: 30:70% and 40:60%-bonded particle board from wood waste AI, AII and fresh wood. (**Optimized innovative variants: V9, V10, and V11 is being patented**) (TF-resin was prepared according to NSR secret recipe. (4% resin in SL and 3% in CL). Figure 28

5. **Group V.** Variants of three layer Rape-bonded particle board from wood waste AI, AII, AI+AI and sawdust SD + garden waste GW wood. (**Innovative variants: V12, V13, V14 and V15**) (Rape emulsion was prepared according to NSR secret recipe (6% Rape in SL and 5% Rape in CL). (will be patented), see Figure 29.

Figure 19. Drying of the wood particles at 75°C.
Figure 20. Laboratory-type blender.

Figure 21. Forming the board, the mixed particles were hand-felted into a frame 70 x 45 cm on metal plate and pre-pressed by hand to form a mat.
Figure 22. The mat was hot pressed using Laboratory press, Siempelkamp.

Figure 23. Trimming the manufactured models of particleboard.
Figure 24. Sanding the manufactured models of particleboard.

Figure 25. Group I. Variants of one layer a combination of TF-resin, PMDI hybrid resin: 30:70% and 40:60% -bonded particle board from wood waste AIII. (V1 and V2).
Figure 26. Group II. Variants of three layer of UF-resin bonded particle board from wood waste AI, AII, AI+AII and from fresh wood (V3, V4, V5, V6).

Figure 27. Group III. Variants of Albumin-protein -bonded particle board from wood waste AI and AII (V7, V8).
Figure 28. Group IV. Variants of three layer a combination of TF-, PMDI hybrid resin-bonded particle board from wood waste Al, AII and fresh wood. (V9, V10, and V11)

Figure 29. Group V. Variants of three layer Rape-bonded particle board from wood waste AI, AII, AI+II and SD + GW. (V12, V13, V14 and V15)
Table 8. Defined parameters of the particle board variants based on wood waste material and bonded by different adhesives

<table>
<thead>
<tr>
<th>Group</th>
<th>Variant</th>
<th>Number of layers</th>
<th>Material</th>
<th>Adhesive System</th>
<th>Density (kg/m³)</th>
<th>Press temperature (°C)</th>
<th>Pressing time factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1</td>
<td>1</td>
<td>All</td>
<td>3 % (70 % PMDI, 30 % TF) (Recipe- Univ. Gö.)</td>
<td>640</td>
<td>200</td>
<td>12 s/mm</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td>3 % (60 % PMDI, 40 % TF)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>3</td>
<td></td>
<td>A II</td>
<td>SL: 10 % UF + 0,5 % AS CL: 8 % UF + 2 % AS</td>
<td>640</td>
<td>200</td>
<td>12 s/mm</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td></td>
<td>A I</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>5</td>
<td></td>
<td>SL: A I, CL: A II</td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td></td>
<td>SW</td>
<td></td>
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</tr>
<tr>
<td>III</td>
<td>7</td>
<td>3</td>
<td>A I</td>
<td>SL: 10 % Albumin-protein resin CL: 8 % Albumin-protein resin</td>
<td>640</td>
<td>200</td>
<td>10 -12 s/mm</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1</td>
<td>All</td>
<td>10 % Albumin-protein resin</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>9</td>
<td>3</td>
<td>SW</td>
<td>SL: 4 % (60 % PMDI, 40 % TF) (Recipe NSR) CL: 3 % (60 % PMDI, 40 % TF) (Recipe NSR)</td>
<td>640</td>
<td>200</td>
<td>12 s/mm</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td></td>
<td>A I</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>11</td>
<td></td>
<td></td>
<td>SL: 4 % (70 % PMDI, 30 % TF) (Recipe NSR) CL: 3 % (70 % PMDI, 30 % TF) (Recipe NSR)</td>
<td>640</td>
<td>200</td>
<td>12 s/mm</td>
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<td></td>
</tr>
<tr>
<td>V</td>
<td>12</td>
<td>3</td>
<td>A I</td>
<td>SL: 6 % Rape resin (NSR recipe) CL: 5 % CP- Rape resin (NSR recipe)</td>
<td>640</td>
<td>200</td>
<td>30 s/mm</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td></td>
<td>A II</td>
<td></td>
<td></td>
<td></td>
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</tr>
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<td></td>
<td>14</td>
<td></td>
<td>SL: A I, CL: A II</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15</td>
<td></td>
<td>SL: SD, CL: GW</td>
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</tbody>
</table>

SL= Surface layer; CL= Core layer; SD= saw dust from the Construction site; GW= Garden waste; SW= Fresh wood chips from softwood (spruce); AI= Untreated massive wood waste; AII= Slightly treated wood waste (issued from glued, coated and varnished scrap wood with coatings not containing halogenated organic compounds or preservation agents).

**Determination of the physical- and mechanical properties of the manufactured models of particleboards**

**Physical properties; Moisture Content, Density, Water absorption and Thickness swelling**

Moisture content, density, water absorption and thickness swelling were determined according to European Norms (EN: 2010) (DIN, 1999) [Moisture Content (EN 322), Density (EN 323), Water absorption (EN 52351), and Thickness swelling (EN 317)]. For density, water absorption and thickness swell-test, the particleboard was cut into 5 cm x 5 cm squares (The test specimensFigure 30) and soaked (immersed) in water at room temperature for 2 and 24 h (Figure 31).
Specimen’s thickness and weight were measured before soaking and after 2 and 24 h of water immersion to determine the short-term and long-term water absorption and thickness increase (Figure 32). The results of water absorption and thickness swelling after 2 and 24 h were expressed as a percentage of the original state.

**Figure 30.** The specimens for density, water absorption and thickness swell- test.

**Figure 31.** Soaking specimens in water at room temperature for 24 h.

**Figure 32.** Specimen’s thickness and weight were measured before soaking and after 24 h of water immersion to determine the water absorption and thickness swelling.

*Mechanical properties; Static bending strength test and internal bond.*

Particleboards of the manufactured Models were cut into 5 cm x 41 cm (thickness x 20+5) rectangular sections for determining static bending strength (Three-point
static bending perpendicular to board surfaces) (Figure 33), and 5 cm x 5 cm squares for internal bond (IB) strength measurements (Figure 34). To determine the internal bond, a 5 cm square sample of board is glued between two wood blocks. The blocks are then pulled apart and the load to failure is recorded (Figure 35).

Mechanical properties were determined according to the European standards method (EN: 2010) [Static bending strength test (EN 310) and internal bond (EN 319)] using a Zwick/Roell 10 testing machine. The crosshead speeds were 5 mm/min for the static bending and IB tests. Modulus of elasticity (MOE) (Figure 36) and internal bond strength (IB) were recorded. After static bending test, the specimens of moisture content were cut from the ends of the bending specimens, and the moisture content was determined according to the European Norms EN 322 (EN: 2010).

Figure 33. Samples for determining static bending strength (EN 310).

Figure 34. Samples for determination of internal bond (IB) strength (EN 319).
Figure 35. Determination of internal bond (IB) strength (EN 319).
Determination of the Formaldehyde Release

The formaldehyde release from the manufactured models of particleboards was determined according to European Norms (WKI-flask- method, EN717-3) and the extractable formaldehyde according to the perforator method (EN 120).

A 2.5 cm square samples were cut from the manufactured particleboards models (Figure 37) for the determination of extractable formaldehyde (acc. EN 120, Figure 38) and formaldehyde release (acc. EN 717-3 (3h and 24h, Figure 39) of the manufactured PB models. Moreover, the moisture content of the test samples after conditioning was determined.
Figure 37. Samples for the determination of extractable formaldehyde and formaldehyde release of the manufactured PB models.

Figure 38. Determination of extractable formaldehyde acc. to perforator method, EN 120 from the manufactured PB models.
Results and Discussion

Mechanical Properties

The average values and variation coefficient of internal bond strength, static bending strength and modulus of elasticity of the fifteen manufactured variants of particleboard are given in Table 9 and illustrated in Figures: 40, 41, 42.

*Internal bond strength:*
- The results in Table 9 and Figure 40 demonstrate that three-layered particleboards manufactured from wood waste type A1 and bonded by UF-resin as a conventional adhesive system (variant no. 4) have achieved the
highest internal bond strength values with 0.42 N/mm² followed by a combination of TF and PMDI hybrid resin: 30:70% and 40:60%. bonded particleboards (variant no. 10 and 11) with IB values of 0.41 N/mm² and 0.40 N/mm² respectively.

- Furthermore, the table demonstrates that the particleboard variants no. 4, 10 and 11 achieved the required value of 0.35 N/mm² for particleboards type P2 (EN 319 (2010); P2: non load-bearing panel for interior use in dry conditions). However, the results of variants no. 4, 10 and 11 are more than 20%, 17% and 14.3% respectively over the requirement of the standard. While the three-layered particleboards manufactured from fresh wood and bonded by a combination of TF, PMDI hybrid 40:60% (variant no.9) had IB value of 0.52 N/mm², which comply with the specifications of European standard EN 312 (2010).

- It can be noted from Table 9 that one-layer particleboards manufactured from wood waste type AI and bonded by combination of TF and PMDI hybrid resin: 30:70% and 40:60% (variant no. 1 and 2) had IB values of 0.41 N/mm² and 0.45 N/mm² respectively. The IB values of the particleboards: variant 1 and 2, complied with the specifications of European standard EN 312 (2010). They fulfilled the requirement for interior fitments (including furniture) for use in dry conditions (Type P2).

- The three-layered particleboards manufactured from wood waste type AI, AI+AI and fresh wood bonded by UF-resin (variant no. 3, 5 and 6) have achieved internal bond strength values of 0.62 N/mm², 0.53 N/mm² and 0.82 N/mm² respectively, which comply with the specifications of European standard EN 312 (2010).

- The Table 9 shows that three-layered particleboards from wood waste type AI bonded by animal’s albumin-protein-resin (variant no. 7) have achieved an internal bond strength value with 0.53 N/mm², which exceeded the required value of 0.35 N/mm² for particleboards type P2 (EN 319 (2010) by more than 50%. While one-layer particleboards from wood waste type AI bonded by animal’s albumin-protein-resin (variant no. 8) had an internal bond strength value with 0.48 N/mm², which comply with the specifications of European standard EN 312 (2010).

- The results in Table 9 demonstrate that three-layered particle boards from wood waste type AI bonded by a rape resin (variant no. 12) have achieved the highest internal bond strength values in the group V with 0.39 N/mm², while three-layered particle boards from wood waste type AI in the surface layers and wood waste type AI in the core layer bonded by a rape resin (variant no. 14) have achieved the internal bond strength values with 0.35 N/mm². Furthermore, the particle board variants no. 12 and no. 14 do always achieve the required value of 0.35 N/mm² for particle boards type P2. However, the results of variant no. 12 are more than 11.4% over the requirement of the standard.
It can be seen from Table 9 that three-layered particle boards from wood waste type AII bonded by a rape resin (variant no. 13) have achieved the internal bond strength values with 0.29 N/mm², which fulfills the requirement for particle boards type P1 for general purposes for use in dry conditions. The lowest internal bond strength value in the group V [0.18 N/mm²] was reported with three-layered particle boards from saw dust in the surface layers and garden waste in the core layer bonded by a rape resin (variant no. 15). This board can be considered of special importance for construction and insulation.

**Bending strength and MOE**

Table 9 and Figure 41 and Figure 42 present the obtained results of static bending strength and MOE as a function of the used binder systems (TF-, PMDI hybrid resins, UF-resin) and wood waste type AI. TF-, PMDI hybrid resin: 30:70% bonded particleboards (variant no. 10) show the highest flexural properties with bending strength of 11.0 N/mm² and MOE values of 2157 N/mm² followed by UF-resin bonded particle board (variant no. 4) with bending strength of 10.43 N/mm² and MOE: 2078 N/mm² and TF-, PMDI hybrid resin: 40:60% (bending strength: 10.1 N/mm² and MOE: 2103 N/mm²).

As a function of the binder system the bending properties of the produced particle boards vary but still all three different variants fulfill the requirement for MOE and exceed the required value of 1600 N/mm². But not all variants achieve the minimum requirement of bending strength except variant no. 10 (TF-, PMDI hybrid resin: 30:70% bonded particleboards). Furthermore, the achieved MOE values of the particleboard variants are 30 % to 35 % over the minimum requirement of 1600 N/mm².

It can be summarized that the variant no. 10 shows sufficient mechanical properties and fulfills the standards of EN 310:2010 and EN 319:2010 for particle boards type P2. However, as mentioned before, variant no. 4 and no. 11 showed values slightly below the minimum requirement of bending strength listed in EN 310:2010 for particle boards type P2 but in consideration of the high MOE values of them the achieved values of static bending strength can be evaluated as acceptable.

Moreover they fulfilled the requirement for particleboard type P1 for general purposes for use in dry conditions. Particleboards bonded by a combination of TF resin and PMDI (variant no. 4 and no. 11) show comparable flexural properties to those bonded by UF-resin as a conventional adhesive system (variant no. 4).

It can be noted from Table 9 that one-layer particleboards manufactured from wood waste type AII and bonded by combination of TF, PMDI hybrid resin: 30:70% and 40:60% (variant no. 1 and 2) had bending strength of values of 8.4 N/mm² and 8.7 N/mm² respectively which were below the minimum requirement of bending strength listed in EN 310:2010 but in consideration of the high MOE values of them (1957 N/mm² and 1827
N/mm² respectively) the achieved values of static bending strength can be evaluated as acceptable.

The three-layered particleboards manufactured from wood waste type AI+AIL and fresh wood bonded by UF-resin (variant no. 5 and 6) have achieved static bending strength values with 12.3 N/mm² and 18 N/mm² respectively, as well as had MOE values with 2213 N/mm² and 3067 N/mm² respectively. They complied with the specifications of European standard EN 312 (2010) and fulfilled the requirement for interior fitments (including furniture) for use in dry conditions (Type P2) but the three-layered particleboards manufactured from wood waste AII bonded by UF-resin (variant no. 3) achieved static bending strength value with 9.0 N/mm², which is below the minimum requirement of bending strength listed in EN 310:2010 but in consideration of its high MOE value 2003 N/mm² the achieved value of static bending strength can be evaluated as acceptable.

Table 9 presents the obtained results of static bending strength and MOE as a function of the used animal’s albumin-protein and wood waste type AI, where the three-layered particleboards bonded by animal’s albumin-protein-resin (variant no. 7) showed flexural properties with bending strength of 10.4 N/mm² and MOE values of 1737 N/mm². It can be clearly observed that the produced particle boards fulfill the requirement for MOE and exceed the minimum required value of 1600 N/mm² listed in the standards of EN 310:2010 by 8.6 %. Although, the produced particle boards showed values slightly below the minimum requirement of bending strength for particleboards type P2 listed in EN 310:2010 but in consideration of the good MOE values of them the achieved values of static bending strength can be evaluated as acceptable. Moreover, the static bending strength values of the produced particle boards fulfill the required value of 10 N/mm² for Particle board type P1 specified by EN 312:2010 (Type P1: general purpose boards for use in dry conditions).

It can be summarized that the animal’s albumin-protein bonded particleboard from wood waste type AI shows sufficient mechanical properties to comply with the European standards of EN 310:2010 and fulfills the requirement of particle boards type P2 almost fully and type P1 fully (static bending strength). While one-layer particleboards from wood waste type AII bonded by animal’s albumin-protein-resin (variant no. 8) had bending strength value with 8.2 N/mm² and MOE value with 1514 N/mm², which are below the minimum requirement of bending strength and MOE for particleboard type P2 listed in EN 310:2010.

Table 9 presents the obtained results of MOE as a function of the used Rape resin as a new adhesive system. The three-layered Rape resin bonded
particle boards from wood waste type AI (variant no. 12) obtained the MOE values with 1883 N/mm² and the three-layered Rape resin bonded particle boards from wood waste type AI in the surface layers and wood waste type AII in the core layer (variant no. 14) attained the MOE values with 1663 N/mm². As a function of the binder system the MOE values of the produced particle boards vary but, as a matter of fact, the both variants fulfill the minimum requirement of 1600 N/mm² for MOE and obtain 4 % or 17.8 % higher MOE values than required, respectively.

It can be summarized that the variants no. 1 and no. 2 do show sufficient mechanical properties and fulfill the standards of EN 310:2010 and EN 319:2010 for particle boards type P2 for interior fitments (including furniture) in dry conditions. Although, the produced particle boards of variant no. 12 and no. 14 showed values below the minimum requirement of bending strength for particleboards type P2 listed in EN 310:2010 but in consideration of the good MOE values of them the achieved values of static bending strength can be evaluated as acceptable.

It can also be seen from Table 9 that three-layered particle boards from wood waste type AII bonded by a rape resin (variant no. 13) have achieved bending strength values with 7.1 N/mm² and MOE value with 1440 N/mm², which are below the minimum requirement of bending strength and MOE for particleboard type P2 listed in EN 310:2010. The three-layered particle boards from saw dust in the surface layers and garden waste in the core layer bonded by a rape resin (variant no. 15) had bending strength values with 7.4 N/mm² and MOE value with 1237 N/mm², where this board can be considered of special importance for construction and insulation.

The average values of surface soundness of the manufactured variants of particleboard in group IV (V9, V10, V11) are illustrated in Figure 43, which shows, that the manufactured variants of particleboard: V9, V10 attained surface soundness values [0.98, 0.8 and 0.8 N/mm², respectively] and complied with the specifications of European standard EN 312 (2010).

Table 9: Mean values of internal bond strength, static bending strength and modulus of elasticity of the particle board variants based on wood waste material and bonded by different adhesives.
<table>
<thead>
<tr>
<th></th>
<th>(Recipe Univ-G0)</th>
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<tbody>
<tr>
<td><strong>II</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V3/ AII</td>
<td>UF</td>
<td>642 (VC 0.8%)</td>
</tr>
<tr>
<td>V4/ AII</td>
<td>UF</td>
<td>641.7 (VC 0.6%)</td>
</tr>
<tr>
<td>V5/ AII, AII</td>
<td>UF</td>
<td>642 (VC 0.4%)</td>
</tr>
<tr>
<td>V6/ fresh wood</td>
<td>UF</td>
<td>641 (VC 0.9%)</td>
</tr>
<tr>
<td><strong>III</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V7/AI</td>
<td>Albumin-protein resin</td>
<td>640 (VC 0.5%)</td>
</tr>
<tr>
<td>V8/AII</td>
<td>Albumin-protein resin</td>
<td>640 (VC 0.2%)</td>
</tr>
<tr>
<td><strong>IV</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V9/fresh wood</td>
<td>TF-, PMDI (40:60%) (Recipe NSR)</td>
<td>640.3 (VC 0.6%)</td>
</tr>
<tr>
<td>V10/ AII</td>
<td>TF-, PMDI (30:70%) (Recipe NSR)</td>
<td>641.2 (VC 0.6%)</td>
</tr>
<tr>
<td>V11/ AII</td>
<td>TF-, PMDI (40:60%) (Recipe NSR)</td>
<td>642 (VC 0.6%)</td>
</tr>
<tr>
<td><strong>V</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V12 Raps AII</td>
<td>Rape resin (6:5%)</td>
<td>642 (VC 0.9%)</td>
</tr>
<tr>
<td>V13 Raps AII</td>
<td>Rape resin (6:5%)</td>
<td>683 (VC 0.7%)</td>
</tr>
<tr>
<td>V14 Raps AI/AII</td>
<td>Rape resin (6:5%)</td>
<td>641 (VC 1.0%)</td>
</tr>
<tr>
<td>V15 Raps SD/GW</td>
<td>Rape resin (6:5%)</td>
<td>697 (VC 1.0%)</td>
</tr>
<tr>
<td>Requirements EN 312:2010 P2 &gt;13 to 20 mm</td>
<td></td>
<td>5-13</td>
</tr>
<tr>
<td>Requirements EN 312:2010 P1 &gt;13 to 20 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>24</td>
<td>3</td>
</tr>
</tbody>
</table>

Values are arithmetic mean values of n= Number of samples; VC = variation of coefficient; EN 312:2010; Particle board type P2: Boards for interior fitments (including furniture) for use in dry conditions; type P1: Boards for general purposes for use in dry conditions
Figure 40. The average values of internal bond strength of the manufactured variants of particleboard.

Figure 41. The average values of static bending strength of the manufactured variants of particleboard.
Figure 42. The average values of modulus of elasticity of the manufactured variants of particleboard.

Figure 43. The average values of surface soundness of the manufactured variants of particleboard (group IV: V9, V10, V11).
Physical Properties

The average values and variation coefficient of thickness swelling (24h), water absorption (24h) of the fifteen manufactured variants of particleboard are presented in Table 9 and illustrated in Figure 44 and Figure 45:

- According to Table 10 the performance of the TF/PMDI binder: 30:70% (variant no. 10) achieve with 8.93% the best swelling behavior followed by TF-, PMDI hybrid resin: 40:60% bonded particleboards with a measured thickness swelling of 10.65 % and exceeded by variant no. 4. Particleboard variant no. 4, UF-resin bonded particleboards show a swelling behavior of 16.17 %. Table 10 shows an overview about the measured water absorption values (24 h). The particleboards only bonded with TF-, PMDI hybrid resin: 30:70% and 40:60% bonded particleboards (variant no. 10 and 11) show a water absorption of 26.88 % and 30.56 %, after 24 h of water soaking, respectively. The particleboards bonded by UF resin show with 51.5 % the worst behavior, compared to these other variants. Variant no. 4 behaves poorly against water soaking. There are no defined limits in the European standards for thickness swelling (24 h) or water absorption (24 h) of particle boards. However, the values of thickness swelling and water absorption obtained in the current study are lower than values reported about similar produced three-layered particleboards based on wood residues (Zhongli et. al., 2006; Nazerian et. al, 2011; Nasser, 2012). Moreover, the thickness swelling value of TF-, PMDI hybrid resin bonded particleboards (variant no. 10 and 11) is better than the required value for Particle board type P4 (15%) specified by EN 312:2010 (Type P4: load-bearing boards for use in dry conditions). While the three-layered particleboards manufactured from fresh wood and bonded by a combination of TF, PMDI hybrid 40:60% (variant no.9) had a thickness swelling of 10.6 and a water absorption of 29.5 %, after 24 h of water soaking, which are a very good values.

- It can be noted from Table 10 that one-layer particleboards manufactured from wood waste type AII and bonded by combination of TF, PMDI hybrid resin: 30:70% and 40:60% (variant no. 1 and 2) had obtained thickness swelling values (24h) of 12.1 % and 11.1 % respectively as well as they achieved water absorption values (24h) of 28.8 % and 27.8 % respectively.

- The three-layered particleboards manufactured from wood waste type AII, A1+AII and fresh wood bonded by UF-resin (variant no. 3, 5 and 6) have achieved thickness swelling values (24h) of 16.9 %, 15.7 % and 10.4 % respectively as well as they obtained water absorption values (24h) of 57.6 %, 50.7 and 38.6 % respectively.

- Mean values and variation coefficients of thickness swelling (24 h) and water absorption (24 h) of the animal’s albumin-protein bonded particleboards are presented in table 9. According to Table 10, the three-layered particleboards from wood waste type AII (variant 7) achieved
thickness swelling value of 29% and water absorption value of 89.3%. While one-layer particleboards from wood waste type AII bonded by animal’s albumin-protein-resin (variant no. 8) had thickness swelling value of 27.6 % and water absorption value of 87.9 %, such as thickness swelling and water absorption can be improved by using a hydrophobic agent.

There are no defined limits specified by the European standards (EN 312:2010) for thickness swelling (24 h) or water absorption (24 h) of particleboard type P2. However, the values of thickness swelling and water absorption obtained in the current study are lower than values reported about similar produced three-layered particleboards bonded by protein isolated from animals sources or vegetable sources (wheat or soy) [McKillip 1989; Liu and Li 2004; Li et al. 2004; Rogers et al. 2004; Liu and Li 2007; Nahla et al. 2007; Huang and Li 2008; Foong et al. 2008; Nordqvist 2009; Khosravi, 2011; Nikvash et al. 2012, 2013].

- Mean values and variation coefficients of thickness swelling after 24 h and water absorption after 24 h of the Rape resin bonded particleboard variants are presented in Table 10.

According to Table 10, The three-layered Rape resin bonded particle boards from wood waste type AI (variant no. 12) achieved the thickness swelling values with 19.8% and the three-layered Rape resin bonded particle boards from wood waste type AI in the surface layers and wood waste type AII in the core layer (variant no. 14) attained the thickness swelling values with 18.9%. Table 10 shows an overview about the measured water absorption values after 24 h, where variant no. 12 obtained a water absorption of 65.2 % and variant no. 14 recorded water absorption of 59.5%.

- According to Table 10, The three-layered particle boards from wood waste type AII bonded by a rape resin (variant no. 13) have achieved the thickness swelling values with 20.9 % and the three-layered Rape resin bonded particle boards from saw dust in the surface layers and garden waste in the core layer (variant no. 15) attained the thickness swelling values with 28 %. Table 10 shows an overview about the measured water absorption values after 24 h, where variant no. 13 obtained a water absorption of 72.9 % and variant no. 15 recorded water absorption of 81.6 %. There are no defined limits in the European standards of EN 310:2010 for thickness swelling (24 h) or water absorption (24 h) of particle board, such as thickness swelling and water absorption can be improved by adding hydrophobic agent.

However, the values of thickness swelling and water absorption obtained by variant no. 12, 13, 14 and variant no. 15 are similar or lower than values reported about similar produced three-layered particleboards bonded by protein isolated from vegetable sources (wheat or soy) [Li et al. 2004; Liu and Li 2007; Nahla et al. 2007; Nordqvist 2009; Khosravi, 2011; Nikvash et al. 2012].
Table 10: Mean values of thickness swelling (24 h) and water absorption (24 h) of particleboard variants based on wood waste material and bonded by different adhesives

<table>
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<tr>
<th>Group</th>
<th>Variant/ wood waste type</th>
<th>Resin type SL/CL</th>
<th>Density kg/m³</th>
<th>Moisture content %</th>
<th>Thickness swelling (EN 317) [%]</th>
<th>Water absorption (DIN 52351) [%]</th>
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<tbody>
<tr>
<td>I</td>
<td>V1/ All TF, PMDI (30:70%) (Recipe Univ-Gö)</td>
<td>640 (VC 0.8%)</td>
<td>5.9</td>
<td>12.1 (VC = 5.6 %)</td>
<td>28.8 (VC = 1.5 %)</td>
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<tr>
<td></td>
<td>V2/ All TF-, PMDI (40:60%) (Recipe Univ-Gö)</td>
<td>643 (VC 0.5%)</td>
<td>6.1</td>
<td>11.1 (VC = 2.6 %)</td>
<td>27.8 (VC = 0.7 %)</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>V3/ All UF</td>
<td>642 (VC 0.8%)</td>
<td>5.0</td>
<td>16.9 (VC = 8.6 %)</td>
<td>57.6 (VC = 5.7 %)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V4/ AI UF</td>
<td>642.5 (VC 0.4%)</td>
<td>5.7</td>
<td>16.17 (VC = 0.19%)</td>
<td>51.5 (VC = 0.13%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V5/ AI, All UF</td>
<td>642 (VC 0.4%)</td>
<td>5.7</td>
<td>15.7 (VC = 3.6 %)</td>
<td>50.7 (VC = 2.4 %)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V6/ fresh wood UF</td>
<td>641 (VC 0.9%)</td>
<td>6.2</td>
<td>10.4 (VC = 4.1 %)</td>
<td>38.6 (VC = 3.6 %)</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>V7/ Al Albumin-protein resin</td>
<td>640 (VC 0.4%)</td>
<td>6.3</td>
<td>29.0 (VC = 1.9%)</td>
<td>89.3 (VC = 1.1%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V8/ AI Albumin-protein resin</td>
<td>640 (VC 0.2%)</td>
<td>6.5</td>
<td>27.6 (VC = 2.9 %)</td>
<td>87.9 (VC = 2.1 %)</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>V9/fresh wood UF</td>
<td>643 (VC 0.6%)</td>
<td>5.6</td>
<td>10.6 (VC = 6.8 %)</td>
<td>29.5 (VC = 0.7 %)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V10/ AI UF</td>
<td>643.7 (VC 0.7%)</td>
<td>5.67</td>
<td>8.93 (VC = 1.7%)</td>
<td>26.88 (VC = 0.07%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V11/ AI UF</td>
<td>643.7 (VC 0.8%)</td>
<td>5.68</td>
<td>10.65 (VC = 0.12%)</td>
<td>30.56 (VC = 0.09%)</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>V12 Raps AI Rape resin (6%:5%)</td>
<td>642 (VC 0.9%)</td>
<td>6.46</td>
<td>19.8 (VC = 2.77)</td>
<td>65.2 (VC = 5.7%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V13 Raps All Rape resin (6%:5%)</td>
<td>683 (VC 0.7%)</td>
<td>6.3</td>
<td>20.9 (VC = 1.9%)</td>
<td>72.9 (VC = 4.2%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V14 Raps AI/All Rape resin (6%:6%)</td>
<td>641 (VC 1.0%)</td>
<td>6.47</td>
<td>18.9 (VC = 1.64%)</td>
<td>59.5 (VC = 5.62%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V15 Raps SD/GW Rape resin (6%:5%)</td>
<td>697 (VC 1.0%)</td>
<td>6.6</td>
<td>28.0 (VC = 1.8 %)</td>
<td>81.6 (VC = 6.5 %)</td>
<td></td>
</tr>
</tbody>
</table>

Requirements EN 312:2010 P2
>13 to 20 mm – 5-13 No requirements No requirements

N 24 3 24 24

Values are arithmetic mean values of n= Number of samples; VC = variation of coefficient; EN 312:2010; Particle board type P2.
Figure 44. The average values of thickness swelling (after 24h) of the manufactured variants of particleboard.

Figure 45. The average values of water absorption (after 24h) of the manufactured variants of particleboard.

**Formaldehyde release and extractable formaldehyde**

The average values and variation coefficient of extractable formaldehyde content (EN 120) and formaldehyde release (EN 717-3, EN 717-1) (3h and 24h) of the fifteen manufactured variants of particleboard are presented in Table 11 and illustrated in Figure 46, Figure 47 and Figure 48):

- The displayed results in the Table 11 show that three-layered particleboards manufactured from wood waste type AI bonded with a combination of TF- and PMDI hybrid resin: 30:70% (variant no. 10) or 40:60% (variant no. 11) show the lowest extractable formaldehyde content and achieved the
same value with 3.1 mg/100 g o. d. board. These results were significantly exceeded by three-layered particleboards manufactured from wood waste type AI bonded with UF resin (variant no. 4) with formaldehyde content of 13.3 mg/100 g o. d. board. The extractable formaldehyde values of the particleboard variants no. 10 and 11 comply with the specifications EN 312 (2010) and the maximum allowed limit value of ≤ 8.0 mg/100 g o. d. board (EPF value is 6.5 mg/100g). The results fulfill the requirement for particleboards of type P2.

The results of variants no. 10 and 11 are 61.3% less than the maximum allowed limit value listed in specifications EN 312 (2010), while the three-layered particle board bonded by UF- resin from wood waste type AI (variant no. 4) did not meet the European standard EN 312 (2010). This is a very good result if we consider that the value of extractable formaldehyde content of the wood waste material type AI was 0.8 mg/100g.

Since there is no standard value specified in the EN 312 (2010) for the formaldehyde release from particle board determined by WKI-flask-method (EN717-3), the obtained flask values of the formaldehyde (3h, 24h) have been converted to their equivalent value in the chamber method (EN717-1) using the correlation between the two methods (Johansson et al., 2013).

It can be seen from the Table 11 that particleboards bonded with a combination of TF-, PMDI hybrid resin: 30:70% (variant no. 10) or 40:60% (variant no. 11) attained the same value of formaldehyde release, 0.1 ppm, which was significantly exceeded by particle boards bonded with UF resin (variant no. 4) with formaldehyde release 0.59 ppm. The achieved formaldehyde release values by particleboard variants no. 10 and 11 comply with the standard value listed in EN 312 (2010), where the maximum allowed limit values are ≤ 0.1 ppm or 0.124 mg/m³ air (Emission class E1).

The results of formaldehyde release after 24 h recorded by variants no. 10 and 11 (0.08 ppm, 0.06 ppm respectively) are less than the maximum allowed limit value listed in EN 312 (2010) with 20%, 40% respectively, while the three-layered particle board bonded by UF- resin from wood waste (variant no. 4) did not meet the European standard EN 312 (2010) which require adding of formaldehyde scavengers for reaching the E1.

Moreover, it is clear from Table 11 that a significant reduction of formaldehyde release with 25% after 24 h could be observed by replacing PMDI with TF from 30% to 40%. In this case the reduction of formaldehyde release can be attributed to tannin acting as scavenger where the formaldehyde is cross-linked with the tannin by high temperature and moisture during pressing (Roffael, 1999).
The values of formaldehyde release (3 h and 24 h) obtained in the current study are similar or lower than the values reported in researches work related to this topic (Lee et. al., 1994; Rosamah, 2003; Essa 2012; Noman et. al., 2014).

- The three-layered particleboards manufactured from fresh wood and bonded by a combination of TF, PMDI hybrid 40:60% (variant no.9) had an extractable formaldehyde content of 4.8 mg/100 g o. d. board and attained the same value of formaldehyde release after 3h, 24h in the chamber method (EN717-1) with 0.1 ppm. The achieved values of extractable formaldehyde content as well as the formaldehyde release after 3h, 24h (EN717-1) meet the European standard EN 312 (2010).

- It can be seen from Table 11 that one-layer particleboards manufactured from wood waste type AII and bonded by combination of TF, PMDI hybrid resin: 30:70% and 40:60% (variant no. 1 and 2) had obtained an extractable formaldehyde content of 9.4, 11.6 mg/100 g o. d. board respectively as well as they achieved formaldehyde release values after 3h (EN717-1) with 0.44 ppm and 0.57 ppm respectively and after 24h with 0.27 and 0.35 respectively. As a result, none of the variants (no. 1 and 2) could meet the European standard EN 312 (2010). This indicates that the University of Göttingen recipe for tannin formaldehyde is not optimal and that the new recipe can be considered superior (variants no. 9, 10 and 11).

- The three-layered particleboards manufactured from wood waste type AII and AI+AII bonded by UF-resin (variant no. 3 and 5) have achieved same value of extractable formaldehyde content with 7.8 mg/100 g o. d. board, and significantly exceeded by three-layered particleboards manufactured from fresh wood bonded with UF resin (variant no. 6) with formaldehyde content of 8.9 mg/100 g o. d. board. The extractable formaldehyde values of the particleboard variants no. 3 and 5 comply with the specifications EN 312 (2010) and fulfill the requirement for particleboards of type P2, while the three-layered particleboard manufactured from fresh wood bonded with UF resin (variant no. 6) did not meet the European standard EN 312 (2010). The three-layered particleboards manufactured from wood waste type AII, AI+AII and fresh wood bonded by UF-resin (variant no. 3, 5 and 6) have achieved formaldehyde release values after 3h (EN717-1) with 0.28 ppm, 0.31 ppm and 0.39 ppm respectively and after 24h with 0.25, 0.25 and 0.30 respectively, so they did not meet the European standard EN 312 (2010).

- The three-layered particleboards bonded by albumin-protein-resin (variant no. 7) have achieved extractable formaldehyde content value with 0.9 mg/100 g o. d. board, which is 88.8% less than the maximum allowed limit value of ≤ 8.0 mg/100 g o. d. board (sliding average value is 6.5 mg/100g) listed in specifications EN 312 (2010) and comply with the specifications EN 312 (2010). The result fulfills the requirement for particleboards of type P2. Moreover, this is a very good result if we consider that the value of
extractable formaldehyde content of the wood waste material type AI was 0.8 mg/100g. It can be seen from the Table 11 that the three-layered particleboards bonded by albumin-protein-resin attained formaldehyde release values after 3h and 24h with 0.01 ppm, 0.00 ppm respectively. While the one-layered particleboard from wood waste type AII and bonded by albumin-protein-resin have achieved extractable formaldehyde content value with 1.6 mg/100 g o. d. board, which is much less than the maximum allowed limit value of ≤ 8.0 mg/100 g o. d. board listed in specifications EN 312 (2010) and comply with the specifications EN 312 (2010) as well as fulfilled the requirement for particleboards of type P2. Moreover, the one-layered particleboard bonded by albumin-protein-resin (variant no. 8) attained formaldehyde release values after 3h and 24h with 0.053 ppm, 0.030 ppm respectively. The achieved formaldehyde release values by albumin-protein-resin bonded particleboard variants no. 7 and 8 comply with the standard value listed in EN 312 (2010), where the maximum allowed limit value are ≤ 0.1 ppm or 0.124 mg/m$^3$ air (Emission class E1). So, animal’s albumin-protein-resin bonded particleboard based on wood waste can be considered as ultra-low formaldehyde release particleboard.

Table 11 displays mean values of extractable formaldehyde content and formaldehyde release (3 h and 24 h) of particleboard variants based on wood waste material and bonded by Rape resin. The obtained results show that the three-layered Rape resin bonded particle boards from wood waste type AI (variant no. 12) or the three-layered Rape resin bonded particle boards from wood waste type AI in the surface layers and wood waste type AII in the core layer (variant no. 14) have achieved a very low value of extractable formaldehyde content with 0.9 and 2.7 mg/100 g o. d. board respectively. The extractable formaldehyde values of the particleboard variants no. 12 and 14 comply with the specifications EN 312 (2010) and the maximum allowed limit value of ≤ 8.0 mg/100 g o. d. board (EPF value is 6.5 mg/100g). The results fulfill the requirement for particleboards of type P2. The results of variants no. 12 and 14 are 88.8%, 66.3% respectively less than the maximum allowed limit value listed in specifications EN 312 (2010). It is a very good result if we consider that the value of extractable formaldehyde content of the wood waste material type AI was 0.8 mg/100g. The behavior of variants no. 12 and 14 according to formaldehyde release after 3h and 24h in the chamber method (EN717-1) is similar to the observed extractable formaldehyde content.

Rape resin- bonded board variant no.12 show the lowest formaldehyde release (0.009 and 0.00 ppm) followed by Rape resin- bonded board variant no. 14 (0.073 and 0.05 ppm). The formaldehyde release values (3h and 24h)
of the particleboard variants no. 12 and 14 comply with the specifications EN 312 (2010) and the maximum allowed limit value of ≤ 0.1 ppm.

The formaldehyde release values (3h and 24h) of variant no. 12 are 91%, 100% respectively less than the maximum allowed limit value listed in specifications EN 312 (2010) as well as of variant no. 14 with 27%, 50% respectively. Therefore, these variants can be considered as ultra-low formaldehyde emission particle board.

- The three-layered Rape resin bonded particle boards from wood waste type AII (variant no. 13) or and the three-layered Rape resin bonded particle boards from saw dust in the surface layers and garden waste in the core layer (variant no. 15) have attained a very low value of extractable formaldehyde content with 3.1 and 0.2 mg/100 g o. d. board respectively. The extractable formaldehyde values of the particleboard variants no. 13 and 15 comply with the specifications EN 312 (2010) and the maximum allowed limit value of ≤ 8.0 mg/100 g o. d. board (EPF value is 6.5 mg/100g). The results fulfill the requirement for particleboards of type P2. The results of variants no. 13 and 15 are 61%, 97% respectively less than the maximum allowed limit value listed in specifications EN 312 (2010). The Rape resin- bonded board variant no.15 show the lowest formaldehyde release after 3h and 24h (EN717-1) (0.00 and 0.00 ppm) followed by Rape resin- bonded board variant no. 13 (0.1 and 0.08 ppm). The formaldehyde release values (3h and 24h) of the particleboard variants no. 13 and 15 comply with the specifications EN 312 (2010) and the maximum allowed limit value of ≤ 0.1 ppm. The formaldehyde release values (3h and 24h) of variant no. 15 are 100% less than the maximum allowed limit value listed in specifications EN 312 (2010). Therefore, the variant no. 15 can be considered as a formaldehyde release free particle board.

Table 11: Mean values of extractable formaldehyde content (EN 120) and formaldehyde release (EN 717-3, EN 717-1) (3h and 24h) of particleboard variants based on wood waste material and bonded by different adhesives

<table>
<thead>
<tr>
<th>Group</th>
<th>Variant/ wood waste type</th>
<th>Resin type SL/CL</th>
<th>Moisture content %</th>
<th>Extractable formaldehyde Perforator method (EN 120:1992) [mg/100 g o. d. board]</th>
<th>Formaldehyde release WKI-flask- method (EN717-3:1996) [mg/1000 g o. d. board]</th>
<th>Chamber value*** (EN717-1) [ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>A 8 (6,5 % M. C.) 3 h 24 h</td>
<td>3 h 24 h</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>V1 / AII</td>
<td>TF, PMDI (30:70%) (Recipe Univ-Gö)</td>
<td>5.9 8,7 9,4 16,2 95,3</td>
<td>0.44 0.27</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>V2 / AII</td>
<td>TF, PMDI (40:60%) (Recipe Univ-Gö)</td>
<td>6.1 11,1 11,6 21,1 119,4</td>
<td>0.57 0.35</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>V3 / AII</td>
<td>UF</td>
<td>5.0 6.6 7,8 10,6 88,1</td>
<td>0.28 0.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>V4 / AII</td>
<td>UF</td>
<td>5.7 12.1 13.3 21.8 145.4</td>
<td>0.59 0.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>V5/AI, All</td>
<td>V6/ fresh wood</td>
<td>V7/AI</td>
<td>Albumin-protein resin</td>
<td>V8/AI</td>
<td>Albumin-protein resin</td>
</tr>
<tr>
<td></td>
<td>UF</td>
<td>UF</td>
<td>UF</td>
<td>UF</td>
<td>UF</td>
<td>UF</td>
</tr>
<tr>
<td></td>
<td>5.7</td>
<td>7.1</td>
<td>7.8</td>
<td>11.8</td>
<td>90.9</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>6.5</td>
<td>1.6</td>
<td>1.6</td>
<td>2.6</td>
<td>24.0</td>
<td>0.053</td>
</tr>
<tr>
<td></td>
<td>5.6</td>
<td>4.3</td>
<td>4.8</td>
<td>7.3</td>
<td>49.4</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>6.46</td>
<td>6.5</td>
<td>0.9</td>
<td>1.0</td>
<td>10.2</td>
<td>0.009</td>
</tr>
<tr>
<td></td>
<td>6.6</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
<td>0.9</td>
<td>0</td>
</tr>
</tbody>
</table>

**≤ 8.0 mg/100 g o. d. board (maximum value); **≤ 6.5 mg/100 g o. d. board (maximum value) as 6 month rolling average.
Formaldehyde tests were carried out as double determinations. EN 312:2010 (Type P2): non load-bearing boards for interior fitments (including furniture) in dry conditions. *** Chamber value was calculated according to the correlation between EN717-1 and EN717-3 (Johnsson et al., 2013).

Figure 46. The average values of extractable formaldehyde and formaldehyde Release (3h and 24h) of the manufactured variants of particleboard.
Figure 47. The average values of formaldehyde Release (3h and 24h) of the manufactured variants of particleboard.

Figure 48. The average values of formaldehyde Release Chamber value (3h and 24h) of the manufactured variants of particleboard.
Summary of results:

Group I) Combination of TF-resin and PMDI according to Göttingen Univ. recipe
Internal bond strength and modulus of elasticity of TF-resin, PMDI one layered-bonded particle boards (V1, V2) comply with the European standard EN 312 (2010) and fulfill the requirements for particle board type P2 except for bending strength, extractable formaldehyde (perforator value) and formaldehyde release. However, the boards achieved a very favorable value of thickness swelling as well as water absorption.

Group II) UF-resin (conventional adhesive system)
Internal bond and modulus of elasticity of UF-resin three layered-bonded particle boards from wood waste type AI and type AII (V3, V4, V5, V6) comply with the European standard EN 312 (2010) and fulfill the requirements for particle board type P2 except for bending strength, extractable formaldehyde (perforator value) and formaldehyde release. But UF-resin three layered-bonded particle boards from fresh soft wood (V6) attained sufficient bending strength.

Group III) Albumin Protein
Internal bond, modulus of elasticity, extractable formaldehyde (perforator value) of albumin protein-bonded particle boards (V7, V8) comply with the European standard EN 312 (2010) and fulfill the requirements of particle board type P2 and P1 (bending strength). Moreover the formaldehyde release and amount of extractable formaldehyde was very low. So, animal’s albumin-protein-resin bonded particleboard based on wood waste can be considered as ultra-low formaldehyde release particleboard.

Group IV) Combination of TF-resin, PMDI (optimized variants NSR-Secret recipe)
In summary, the evaluated physical and mechanical properties as well as extractable formaldehyde and formaldehyde release of the three-layered Particle board bonded with a combination of TF-, PMDI hybrid resin: 30:70% or 40:60% (variants: V9, V10, V11) comply with the standards of EN 312 (2010) and fulfill the requirements of particle board type P1 (general purpose in dry conditions) and P2 (for interior fitments (including furniture) for use in dry conditions). Moreover, the thickness swelling value of TF-, PMDI hybrid resin bonded particleboards (variant no. 10 and 11) is better than the required value for Particle board type P4 (15%) specified by EN 312:2010 (Type P4: load-bearing boards for use in dry conditions).

Group V) Rape resin
Variants 12, 13, 14 and 15 represents three-layered Rape resin bonded particleboards from wood waste type AI, AII, AI+AII, SD+GW. Variant no. 12 and variant no. 14 have achieved internal bond, modulus of elasticity, formaldehyde release and extractable formaldehyde complying with the European standard EN 312 (2010) and fulfill the requirements of particleboard type P2. Bending strength is close to fulfill the requirement of particleboard type P1). Moreover, the
formaldehyde release and extractable formaldehyde of the manufactured variants (V12, V13, V14, V15) were superior, especially for the two variants V12, 15. Consequently, these variants can be considered as ultra-low formaldehyde emission particle board and variant no. 15 can be considered of special importance for construction, insulation purposes and to coat and decorate the inner walls of buildings.

However, further research is needed to develop and optimize a new adhesive system for the manufacturing of wood panels from wood waste based on a protein adhesive extracted from rape seed press cakes.

**A preliminary investigation to extract protein from rape seed press cakes in a simple way.**

*Extraction of protein mixture from the left over cake of rape seed*

30 kg of rape seed press cakes from GUNARSHÖGS GÅRD AB (Figure 49) were pulverized using a small mill (Coffee grinder, Andersson, Figure 50) and transferred to Göttingen University where five variants of particle board were manufactured using pulverized rape seed press cakes in natural state as an adhesive system.

For the extraction of a protein mixture from rape seed press cakes 4 kg of left over cakes powder (flour) with moisture content 8% was taken (Figure 51) and divided in four parts. Each part was soaked in water with a ratio of 1:4 (w/v), at room temperature. Meanwhile the mixture was continuously stirred 1 hour by an overhead stirrer RW 20 (IKA-WERK) at 300 rpm (Figure 52). The blended mixture was filtered through a cullender (metal sieve) as well as a scrim (cloth bag) to collect solubilized protein (Figure 53).

The remaining solid phase retained on cullender was dried at 70 °C (Figure 54). The mixture was subjected to centrifugation using BECKMAN J2-HS Centrifuge equipped with a six-flasks rotor (Figure 55). The centrifugation was run at 16 000 rpm. (speed) for 10 minutes at 4 °C. The centrifugation process creates three streams (Figure 56): an oil fraction (supernatant cream), an aqueous phase (subnatant), and a solid phase placed on the wall of the flask that primarily consist of three layers: A yellow protein and a light brown protein and a third layer comprising sediments and seeds hulls respectively (Figure 57).

The protein forms the bulk. The oil and aqueous phase were removed and the solid phase was collected and dried at 45 °C for 18 hours to the moisture content 35% (1012.5 g = 750 g dry weight) and cut into small species using a spatula (Figure 58) and then used as an adhesive for manufacturing particle board. We conclude that the amount of protein extracted, including sediments and seeds hulls, is 20 % of the rape seed press cakes.
Board manufacturing

Medium density three layers particleboards were fabricated by using the extracted protein as an adhesive (Solution protein: water, 1:3) (Figure 59). Wood particles from wood waste type AII were used. Wood particles of SL and CL were oven dried at 75°C using drying cabinet to reach approximately 2% moisture content (Figure 60). Constant weight of particles was weighted to obtain the targeted final bulk density of 0.65 g/cm$^3$ and thickness of 19 cm. The wood particles were mixed (blended) with protein adhesive using a laboratory-type blender (Figure 61). Immediately, the mixed particles were hand-felted into a frame 50 x 30 cm on a metal plate and pre-pressed by hands. Thereafter, the frame was removed to get the mat (Figure 62), which was hot pressed by 200 °C for 15 minutes using a laboratory press, model Siempelkamp (Figure 63). The pressed particleboard was then trimmed (450 mm x 250 mm) to avoid edge effects (Figure 64). The manufacturing conditions of the three-layered particleboard are listed in Table 12. Due to the high press factor, it was not meaningful to determine the properties of the manufactured board.

Table 12: Defined parameters of particleboard manufacturing based on wood waste material and bonded by protein

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Particle board variant no. 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resin type</td>
<td>Animal’s albumin-protein resin prepared according to the University of Göttingen own recipe</td>
</tr>
<tr>
<td>Quality of particles</td>
<td>wood waste material Type AII</td>
</tr>
<tr>
<td>Number of boards</td>
<td>1</td>
</tr>
<tr>
<td>Layers</td>
<td>3</td>
</tr>
<tr>
<td>Mass percentage surface layer (%)</td>
<td>40</td>
</tr>
<tr>
<td>Mass percentage core layer (%)</td>
<td>60</td>
</tr>
<tr>
<td>Particle size surface layer (mm)</td>
<td>&gt; 0,2 ≤1,0</td>
</tr>
<tr>
<td>Particle size core layer (mm)</td>
<td>&gt; 1,0 ≤4,0</td>
</tr>
<tr>
<td>Target density (kg/m$^3$)</td>
<td>650</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>19</td>
</tr>
<tr>
<td>Board format (trimmed, mm)</td>
<td>450 x 250</td>
</tr>
<tr>
<td>Press Temperature (°C)</td>
<td>200</td>
</tr>
<tr>
<td>Press time factor (s/mm)</td>
<td>47</td>
</tr>
<tr>
<td>Moisture content particles before pressing %</td>
<td>32%</td>
</tr>
<tr>
<td>Surface layer - resin content (% solid content based on oven-dry weight of the wood particles)</td>
<td>6% (5% protein + 1% sediments and seeds hulls)</td>
</tr>
<tr>
<td>Core layer - resin content (% solids resin / oven-dry particles)</td>
<td>6% (5% protein + 1% sediments and seeds hulls)</td>
</tr>
</tbody>
</table>
Figure 49 Rape seed press cakes from GUNARSHÕGS GÅRD AB

Figure 50. The rape seed press cakes were pulverized using a small mill (Coffee grinder, Andersson).
Figure 51. 4 kg of rape seed press cake powder (flour) with moisture content 8%.

Figure 52. Rape seed press cake powder was soaked in water with a ratio of 1:4 (w/v), at room temperature and stirred 1 hour by an overhead stirrer RW 20 (IKA-WERK) at 300 rpm.
Figure 53. The blended mixture was filtered through normal metal cullender as well as scrim (cloth bag) to collect solubilized protein.

Figure 54. The remaining solid phase retained on the cullender was dried at 70 °C.
Figure 55. Centrifugation using BECKMAN J2-HS Centrifuge equipped with a six-flasks rotor (16,000 rpm., 10 min., 4 °C.)

Figure 56. The centrifugation process creates three streams: an oil fraction (supernatant cream), an aqueous phase (sub-natant), and a solid phase placed on the wall of the flask.
Figure 57. The solid phase consists of three layers: A yellow protein and a light brown protein and a third layer comprising sediments and seeds hulls respectively. The protein forms the bulk. The oil and aqueous phase were removed.

Figure 58. The solid phase was collected and dried at 45 °C for 18 hours to the moisture content 35% (1012.5 g = 750 g dry weight) and cut into small species using a spatula.
Figure 59. Adhesive preparation using the extracted protein (Solution protein: water, 1:3).

Figure 60. Wood particles from wood waste type AII were used. Wood particles of SL and CL were oven dried at 75°C using a drying cabinet to reach approximately 2% moisture content.
Figure 61. The wood particles were mixed (blended) with protein adhesive using a laboratory-type blender.

Figure 62. The mixed particles were hand-felted into a frame 50 x 30 cm on metal plate and pre-pressed by hands. Thereafter, the frame was removed to get the mat.
Figure 63. The mat was hot pressed by 200 °C for 15 minutes using a laboratory press, model Siempelkamp.

Figure 64. The Protein bonded particle board after trimming
Conclusions:
The protein extraction method is good but needs to be developed through the following:

1. Improve the filtering process.
2. Analysis of the components of aqueous extraction (moisture content, oil content, protein content).
3. Improved separation of protein from oils, impurities, sediments and seeds hulls and characterization of the protein.
4. Isolation and determination of protein types (Cruciferin, Globulin, Napin, Albumin, Oleosin).
5. Search for a technique to extract the insoluble protein mixed in water.
6. Find additives to reduce protein swelling with water and reduce the use of water. Thus reducing the press factor.
7. Investigate the possibilities to add dispersion materials such as sodium hydroxide to spray the protein homogeneously on the wood particles.

The isolated rape-protein can be used as binder for particleboard. However, to expose the protein’s best possible properties for this application, they have to be processed to reduce protein swelling with water and reduce the use of water, thus to reduce the press factor as well as to spray the protein on the wood particles homogeneously.

It is an advantage to extract protein from the rape seed press cakes. Furthermore, the extraction process and the gluing process of the wood particles have to be developed and optimized. Therefore, further studies should be performed to obtain a better understanding of protein behavior and improve its performance as a binder for particleboards.

We recommend further research work to develop and optimize a new adhesive system for the manufacturing of wood composites based on protein extracted from rape seed press cakes. We also recommend launching a project aiming at developing and manufacturing such an innovative rape-protein adhesive.

Separation of wood waste at construction sites
One part of the project has been to look at strategies and methods for separation and collection of wood waste at construction sites, from a commercial, technical and recycling point of view. This part of the project has been carried out in cooperation with MTA Bygg och Anläggning AB and included site visits and compiling of waste statistics from a number of construction sites and discussions/proposals for improvement of the waste separation, adopted to the project specific conditions. Examples of transport documents and labels for containers with different waste types have been presented.
**Swedish amounts of wood waste**

The amount of wood waste, collected and treated in Sweden is around 2 million tons/year. Out of this 85-90% is incinerated for the production of heat and electricity. Just a random part, ca 22 000 tons/year is recycled as material or used for composting or biogas production (SCB, Official Statistics, 2019). See Table 1. A part not accounted for goes to the second hand market instead of being included in some of the waste streams.

Wood waste can be categorized as “pre consumer waste” or “post consumer waste” (M Erlandsson, J.O Sundkvist, Environmental consequences of different recycling alternatives for wood waste, IVL 2014).

Pre-consumer waste is defined as spillage from renovation and new constructions. This type of waste is produced during the whole building process and can contain fresh wood of a high quality, when sorted and kept correctly. The amount of pre consumer waste tends to diminish, due to increasing use of pre-fabricated building elements, custom designed for each project.

Post-consumer waste comes from demolition of buildings or parts of constructions. This type of waste has been subject to different kinds of degradation due to weather, long use etc and has a variable quality, which makes it more difficult to recycle.

**Guidelines for waste from construction sites**

As a part of the process to achieve a building or demolition permit the construction company needs to present a control plan including data on handling of waste (primarily hazardous waste). According to the general environmental law (“miljöbalken”) all handling of waste should follow the waste hierarchy, which means reduce, reuse or recycle when possible and incinerate or landfill only when there are no other options.

There are also guidelines from the Swedish Construction Federation (Svensk byggindustri), providing examples of routines, practical advices for source separation and a “bottom line” regarding waste management that should be complied with at all construction and demolition sites. The recommendations, updated in May 2019, states that separation of wood waste should always be included at all construction sites:

- Packaging material, including standard pallets should be sorted out for reuse, systems are available, see [www.byggpall.se](http://www.byggpall.se),
- Other wood waste should be sorted for recycling and separated from hazardous wood waste (i.e impregnated wood),
- Wood that cannot be separated should be sorted as burnable waste.

See more at “Svensk Byggindustri” homepage:
Example, sorting of construction waste, Knäred, MTA Bygg och Anläggning

In Knäred, Laholm, MTA renovated a municipal home for elderly people with 5 apartments during 2019. New roof, partly new inner walls, new coatings, new kitchens.

At a small project like this the number of fractions sorted can be adjusted over time and adapted to the actual phase of the project.

During renovation of the roof bricks and wood were the dominating fractions and therefore sorted out in separate containers. Other fractions, like packaging material (plastic, cardboard, paper) are more frequent in a later stage of the project, but were not separated from the residual waste due to small amounts and lack of space.

The non-hazardous waste was separated in the fractions shown in the table below. 48 % of the waste was separated as recyclable and 52 % was left as mixed/residual waste.

Table 13. Waste separation results, MTA project, renovation of Knäred municipal apartments for elderly people,

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Weight (ton)</th>
<th>%</th>
<th>Fee, SEK/ton</th>
<th>Total waste disposal cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bricks</td>
<td>17,22</td>
<td>34</td>
<td>83,97</td>
<td>1446</td>
</tr>
<tr>
<td>Un treated wood</td>
<td>1,9</td>
<td>4</td>
<td>305</td>
<td>580</td>
</tr>
<tr>
<td>Treated wood</td>
<td>5,06</td>
<td>10</td>
<td>162,85</td>
<td>824</td>
</tr>
<tr>
<td>Mixed waste</td>
<td>26,2</td>
<td>52</td>
<td>1370</td>
<td>35 894</td>
</tr>
<tr>
<td>Transports</td>
<td></td>
<td></td>
<td></td>
<td>44 847 SEK</td>
</tr>
</tbody>
</table>
The fractions of wood and mixed waste were categorized at NSR. The results show that the wood fraction is in principle clean, with some metal nails and screws.

![Image of mixed waste](image1.png)

**Figure 67. Mixed waste and separated wood waste, Knäred construction site, MTA.**

The main fractions in the “mixed waste” fraction were:

- Bricks (from the roof renovation),
- Plastic packaging material,
- Gypsum boards from internal renovation,
- Cardboard from packaging
- Insulation material (mineral wool, rock wool etc),
- Other material (plastic tubes, protection plastic, metal pieces)

*Example, sorting of construction waste, Ängelholm, MTA Bygg och Anläggning*

At another MTA construction site, a new pre-school, kv Rektorn, Ackas gränd in the city of Ängelholm, the situation is similar with respect to waste separation. In this case it is a “green field” construction, including ground works, raising the buildings in prefabricated concrete elements.

![Image of MTA construction site](image2.png)

**Figure 68. MTA Construction site, Pre-school in Ängelhom**
The waste from the site was separated in metals (mainly cut reinforcement bars) and “burnable waste”. During certain periods sorting also included wood, gypsum, cardboard and plastic packaging material. From the table below we can conclude that 63% of the waste was separated for recycling and 36% was left as residual waste.

**Table 14. Waste fractions sorted at MTA project kv Rektorn 3, a new pre-school in Ängelholm**

<table>
<thead>
<tr>
<th>Fractions</th>
<th>EWC-kod</th>
<th>Weight</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burnable waste</td>
<td>Ton 0.5</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Not burnable</td>
<td>Ton 16.9</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>Metals</td>
<td>Ton 5.17</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Gypsum</td>
<td>Ton 6.12</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Isocyanats (haz waste)</td>
<td>08 05 01</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>Wood waste, treated</td>
<td>Ton 18.73</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>Wood waste, untreated</td>
<td>Ton 0.68</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>48.1 tons</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 69. MTA Construction site, Pre-school Ängelholm. Containers for residual waste and metals.**

*Example, sorting of construction waste, Apartment buildings, MTA Bygg och Anläggning*

Waste amounts and possibilities for separation can vary between projects, due to local conditions. Below statistics of waste amounts from two projects, comprising
construction of 48 new apartments, in each project. In project “Järneken” walls and roofs were pre-fabricated and in project “Salmo Salar” only the balconies and staircases were pre-fabricated. In both cases the foundations were in reinforced concrete and fabricated at site.

Waste amounts are shown in the table below. In both project wood was a dominant fraction to recycling, 36 and 19 % respectively. In project “Salmo Salar”, where more concrete constructions were made at site, also the fraction “concrete waste” was considerably higher.

Table 15. Waste fractions sorted at MTA project “Järneken” and “Salmo Salar”, 48 apartments in each project

<table>
<thead>
<tr>
<th>Fractions</th>
<th>Project “Järnkroken”, tons</th>
<th>%</th>
<th>Project “Salmo Salar”, tons</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed waste to external sorting</td>
<td>22.7</td>
<td>21</td>
<td>62.92</td>
<td>35</td>
</tr>
<tr>
<td>Mixed construction waste</td>
<td>1.32</td>
<td>1</td>
<td>1.82</td>
<td>1</td>
</tr>
<tr>
<td>Treated wood</td>
<td>32.51</td>
<td>31</td>
<td>31.92</td>
<td>18</td>
</tr>
<tr>
<td>Untreated wood</td>
<td>5.72</td>
<td>5</td>
<td>1.82</td>
<td>1</td>
</tr>
<tr>
<td>To landfilling</td>
<td>1.72</td>
<td>2</td>
<td>0.69</td>
<td>0.4</td>
</tr>
<tr>
<td>Burnable waste</td>
<td>8.28</td>
<td>8</td>
<td>15.5</td>
<td>9</td>
</tr>
<tr>
<td>Coarse burnable waste</td>
<td>12.11</td>
<td>11</td>
<td>27.4</td>
<td>15</td>
</tr>
<tr>
<td>Impregnated wood</td>
<td>0.92</td>
<td>1</td>
<td>0.58</td>
<td>0.3</td>
</tr>
<tr>
<td>Gypsum</td>
<td>13.46</td>
<td>13</td>
<td>3.36</td>
<td>2</td>
</tr>
<tr>
<td>Concrete waste</td>
<td>8.40</td>
<td>8</td>
<td>33.78</td>
<td>19</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>107.14</strong></td>
<td></td>
<td><strong>179.79</strong></td>
<td></td>
</tr>
</tbody>
</table>

**Drivers for better waste sorting at small construction sites?**

In total it is obvious that the waste management cost is very insignificant, compared with the total project value. The motivation for a more sophisticated source separation at the building site can therefore be rather small.

In the case of Knäred the mixed waste contained quite a lot of inert waste (e.g. crushed bricks) and packaging material, even though bricks were sorted out separately.

Improved sorting routines at projects of this size could include separating packaging material. Also a better discipline in separation of inert waste from the mixed waste can improve the sorting results. The economic value of sorting improvements would probably be small or negative for the contractor. Any change in the sorting routines means costs related to both hired containers, transportation and logistics at the site. At a small site like in Knäred it is difficult to find place for more than 2-3 containers at the same time.
From environmental point of view the value of the separated waste must be compared with the environmental impact of increased transports caused by the separation.

Handling of construction waste at Waste Management Facilities

At a Waste Management Facility normally sorted wood waste as well as inert waste is accepted with a lower fee. Today the wood waste is normally crushed and incinerated and the inert waste is used in constructions with a lower quality demand (internal roads, embankments etc).

The residual, mixed waste is normally separated in a heavy, inorganic fraction, scrap metals and a light fraction, possible to incinerate. Separation of more fractions from mixed waste is done according to the composition of the specific waste. Many times it is difficult to obtain fractions with a quality acceptable for the recycling industry.

Conclusions

A conclusion is that at most construction sites there are favorable conditions for separation of recyclable wood, metals and hazardous waste from residual waste. On the other hand, it is normally difficult physically and logistically to handle more fractions separately, due to lack of space. During different phases of a project also other fractions could and should be handled separately, for example clean and/or contaminated soils from excavations, concreate/bricks during demolition, plastic, cardboard and other packaging materials at the final stage of the construction.

But it is most likely always impossible to avoid a fraction also with residual/mixed waste, even though it can be minimized. This fraction can be sorted and to some extent recycled together with other types of industrial waste at municipal or private waste management sites.

The new guidelines for waste management at construction sites from the Swedish Construction Federation (Svensk byggindustri) can be of good help to improve waste sorting and adopt it to the variable conditions on different projects.

Commercial opportunities

Contacts with furniture producing- and design companies such as Green Furniture, Zenit design, Kinnarps and others show interest in the innovative particle boards variants resulting from this project. Both designers and furniture manufacturers have identified niches for these innovative variants where non-toxic environments are essential, such as in hospitals, schools, kindergarten, offices. The ultra-low formaldehyde release and formaldehyde-free particleboards variants seem to be completely in line with their wishes.

Some particle board-producing companies such as Pfleiderer, Kronospan and Byggelit have also expressed interest in our models. Some adhesive companies such
as Huntsman and Loick Biowertstoff GmbH have also shown interest in the adhesive systems used in the production of our variants. Also some rapeseed press cake producing companies like Kleeschulte and Gunnarshögs have shown great interest in the possible, future use of their products/waste in this field.

All together this interest opens the door for commercial investments in the future.

The project results regarding separation and sorting of wood waste from construction sites indicates both possibilities and restraints in implementation of new commercially viable systems. The size of the building project, the time span of different stages of the building process and also physical constraints and logistical challenges are factors that have to be addressed individually for each construction sites. The low value of recycled wood and the relatively low gate fees at waste disposal sites are other obstacles to consider.

However, more research as well as product-tailored commercialization plans are needed before competitive products can be put on the market. We find that very promising niches for our innovative variants have been identified.

**Environmental aspects on improved recovery of wood waste**

**Background**

Since the 1970s the global CO₂ emissions have increased by 70 percent and the World's total annual emissions of greenhouse gases are estimated at about 49 billion tonnes of carbon dioxide equivalents. From 1990 the increase has been approximately 24 percent.

In Sweden it is mainly domestic road transport that accounts for the most pronounced share of emissions, approximately 34%. This is followed by emissions from industry, electricity and heat production and agriculture. Emissions from residential and commercial buildings account for 6 percent of emissions, while only 3 percent of emissions come from the waste sector.

The waste sector includes fossil carbon dioxide emissions from waste incineration, methane emissions from uncontrolled waste dumps and nitrous oxide emissions from waste incineration and from wastewater management.

Total greenhouse gas emissions in Sweden corresponded to about 59.8 million tons in 2009 converted to carbon dioxide units, while the Swedish emissions of the gas carbon dioxide itself were 46.6 million tonnes during the same year (Bramryd and Johansson 2011).
The natural range of carbon dioxide concentrations in the atmosphere over the last 650,000 years varies between 180-300 ppm, and thus the present values far exceed these values. Over the period 1995-2005 the average growth-rate of the atmospheric carbon dioxide concentrations was about 1.9 ppm per year on an average. (IPCC, 2007). Actions are needed in the urban systems to compensate for increasing concentrations of carbon dioxide, as the natural CO₂ balancing processes are insufficient. Thus it is of great importance to establish carbon accumulating functions in the urban society.

Accumulation of organic carbon in long-lasting structures in the urban society, like in buildings, libraries, etc is also a process that might delay the release of CO₂ to the atmosphere (Bramryd 1982, 1983). It was estimated that this accumulation in long-lasting products amounted to about 2.10 x 10^6 g C per capita in industrialized countries and about 0.15 x 10^6 g C per capita in less industrialized countries, resulting in a total sink of carbon in human houses of over 3500 x 10^{12} g organic carbon (Bramryd 1982, 1983). Particle board is such a carbon accumulating product. If the wood chips would have been incinerated, most of the organic carbon would have been emitted as CO₂.

The use of residues from used particle board material in biological processes, like composting or anaerobic fermentation, is beneficial for the carbon balance. After adding compost or bio-residues to the soil in agriculture, horticulture or forestry, a portion of the organic material is quite resistant to degradation and forms an increasing sink of organic carbon. The use of such soil improvements especially in sandy soils, or in soils with a high clay content, will increase the humus content and thus also improve biomass productivity, resulting in more accumulation of organic carbon (Bramryd, 2001, 2002).

**Life cycle of wood – multiple use and creating eco loops**

**General aspects**

The life cycle of wood products can be summarized in the following stages, each with close relation to climate change and environmental and ecological effects.

a) Ecosystem Services of the growing tree already in the forest,

b) Use of wood for furniture production or other products,

c) Recycling of wood waste and production of wood chips to be used in particle boards,

d) Recycling of particleboards 2-3 times (woodchips re-processed from old particle-board into new particleboards)

e) Final use of fragmented particleboard as filter for waste water, process water or landfill leachates rich in nutrients.

f) Composting the material. Use of the compost as fertilizer in forest
plantations. As an alternative, non-recyclable board could be used for biogas production in systems adopted to extended retention times, e.g. bioreactor cells.

Environmental benefits from using wood chips derived from waste wood include:

a) Less use of virgin wood material, less pressure on forest management

b) Less energy demands for processing and transportation of timber, etc. It also promotes waste reduction, recycling and a circular economy.

Wood waste thus also steps up in the waste hierarchy to “reuse”.

c) When the particle board material no longer can be re-processed to new particle board, it can be used as a filter material for local treatment of e.g. leachates or other waste-water fractions with a high nutrient content. The used wood chips, mixed with nutrients after being used as filter, can be used for biogas production through fermentation or for compost production.

d) The fermentation residues or compost can be used as a non-fossil and low energy demanding soil improvement

e) Organic fertilizers provide addition of humus substances to the soil, and hence increased storage of soil organic matter, in combination with improved water and nutrient holding capacity.

**Effects on the CO₂ balance and climate change**

Wood waste used as raw material for board production means an increased turnover time for the wood material and provides an increased pool of organic carbon stored in furniture and construction material. Even if the total amount of carbon stored in wooden products at each time probably does not increase, the wood material available for other purposes will be higher, for example to substitute material today produced by fossil raw material.

Especially the possibility to re-use the wood chips in the final stage to something else than fuel, will affect the CO₂ balance and provide a carbon sink. Such a final use of the wood material could be as filter for water purification with a following composting of the material and use as soil improvement. This will bring long-lasting organic carbon to the soil and improve the soil capacity as a carbon sink.

As mentioned above, the total amount of wood waste in Sweden being used as biofuel is almost 2 million tons/year (SCB, 2019). The amount of organic carbon in dry wood is approximately 45 % and the mean of water content in wood waste can be estimated to around 20 % (considerable variations due to waste origin and storage conditions). If, theoretically, all this waste wood was used as raw material for production of long-lasting products (including particleboards) it would create a carbon sink equal to (Bartlett et. al. 1994 and M.O.F.I. 2011):
Cm = Bo x C%

Cm: The amount of accumulated organic carbon (ton).
Bo: Amount of wood wastes (ton).
C%: The percentage of organic carbon in the wood = 45%

Cm = 0,8 x 0,45 x 2 = 0,72 million tons of organic carbon/year.

We conclude that the amount of accumulated organic carbon in wood waste in Sweden is approximately 0,7 million tons/year., When/if this amount of carbon is burnt or completely decomposed aerobically the emission of CO₂ would be around 2,8 million tons. In comparison, the total amount emission of greenhouse gases in Sweden was 52,7 million tons of CO₂-equivalents 2017 (Naturvårdsverket, 2019).

If all the particleboards produced in Sweden, around 500 000 m³/year, equivalent to approx. 325 000 tons/year (density around 0,65 tons/m³) had been manufactured from wood wastes instead of virgin forest biomass, this could theoretically contribute to a decrease the carbon dioxide emission in Sweden with some 0,5 million tons, which is almost 1 % of the total CO₂ emission in Sweden per year.

**Climatic effects**

The process of wood recycling into new products, like particleboard, means that the material is used in a higher level of the “waste hierarchy” decided by the EU and implemented by the Swedish Government. It also contributes to fulfil international climatic goals for decreasing CO₂ emissions and creating more carbon sinks in the environment.

**Health and sustainability aspects**

Urea-formaldehyde, commonly used as a binder in particle board, can cause allergic effects to people coming into contact with the product, or even be carcinogenic. Thus when tannins are used to replace formaldehyde as binding agent major positive medical effects are achieved. Tannins are also of a biogenic origin, being extracted from renewable forest resources. This is positive from an eco-cycling point of view. Moreover, natural adhesive system based on for example albumin-protein are required to reduce and eliminate the formaldehyde emission into the air from particle boards.

**Fibre material as adsorbent for nutrients and use as soil improvement**

Fibre material that has been used, perhaps in several cycles, in board material finally is not any longer suitable as raw material for the production of new boards. Such fibre material can be used as filter material during waste water treatment or for landfill leachate purification. With the supply of nitrogen and phosphorus through the eutrophicated water bacterial growth is stimulated, using the fibre material as an energy source for the microorganisms. In this way nutrients are immobilised in
the bacterial biomass. When the fibre filter is saturated with nutrients it can be used as soil improvement.

Except adding nutrients to the soil, also a major amount of humus-forming fibre material is added, positively contributing to the long-term storage of organic carbon in the soil. Thus the recycling of waste wood as raw material in board production, and thus giving a prolonged life of the organic matter, also has a “down-stream-effect” with increased contents of organic carbon in soils when fibre derived material finally is added. In addition to immobilization of nutrients into a bacterial biomass, the fibre material has a large active surface and can bind up base cat-ions like Ca, Mg, K, and others by forming complex bindings. With these two effects combined the fibre material is extremely useful for extracting nutrients from e.g. leachates or other types of wastewater rich in nutrients.

Beds of fibre material like saw dust and wood chips can significantly reduce the amount of nutrients in infiltrated, eutrophicated water (Bramryd 2002). By using the produced fibre derived compost as soil improvement in e.g. forests and forest plantations several benefits are achieved. In addition to creating an eco-loop by returning nutrients in the fibre material to the forest, addition of organic matter to sandy forest soils improve the water and nutrient holding capacity of the soil, stimulating the production of new forest biomass, that can be used in forest industry. Residues from fibreboard- and particle board production can also be used as a substrate in horticulture and green-houses as a substitute for peat in e.g. paper pots.

By substituting peat, which is regarded as a semi-fossil material, clear benefits can be made from a CO₂ and climatic point of view. Used fibre material, no longer suitable for board production, can also act as a substrate for bio coal production. About 50 % of the organic carbon remains after the pyrolysis process as charcoal resistant to biological degradation. In addition to building up a sink of long-lived organic carbon in the soil, bio-coal also has a good capacity of retaining nutrients by forming chemical complexes to the surface. Thus the nutrient holding capacity of the soil is increased and leaching effects minimized. With a good ability to form metal complexes the fibre material is also relevant to use as adsorbent for heavy metal contaminated water or water containing petroleum spillage. If this material then is landfilled under anoxic conditions and in the presence of small amounts of sulphates, the heavy metals are also firmly bound up as metal sulphides. Fibre material can also be used as adsorbent for water polluted with heavy metals or petroleum spillages.

**Life cycle aspects in forestry**

Harvesting and processing of wood from modern forestry is often very energy demanding, often including diesel engines during the harvest as well as long transportation distances for the loggings. In addition to this, often commercial fertilizers are needed for optimal growth of the forest. Many of the components in commercial fertilizers, like phosphorus, are transported from other continents and
the production of nitrogen fertilizers, like ammonium and nitrate, often includes the very energy demanding Haber-Bosch technique where atmospheric nitrogen is fixed with electrical power. Thus, large amounts of energy can be saved using waste wood as a resource for the production of new board products. By using waste wood, the forest resources are also saved for other purposes. For example, if the use of wood as construction material for new houses, to create urban carbon sinks, is increased the virgin timber resources find a market where recycled wood cannot be used. An increasing market for wood as a substitute for fossil plastics (cutlery, plates, etc) will also increase the need for wood resources.

The virgin wood resources thus can be used for products where waste wood would be difficult to use. A decreased pressure on Swedish forestry production can also increase sustainability parameters like species diversity, resulting from e.g. less use of commercial fertilizers and perhaps allowing the forests to get a higher age before harvest and thus allowing a higher volume of stored organic carbon at each time unit.

Conclusions, utilization and next step

Conclusions

1- The ordinary NSR machinery (crusher and drum-sieves) for large-scale sorting/crushing of wood waste also serves well for production of high-quality wood chips type AI and AII as raw material for particle boards. The efficiency was increased and the amount of gravel and impurities [0.61%] decreased significantly compared with that reported in the pilot project (RE:source no. 42507-1) [4.83%] due to good sorting of the wood waste and choice of most suitable mesh sieve. Also, a better handling of the wood waste and the produced wood chips, to avoid gravel and stones from the site, during the loading of the machines improved the quality of the wood chips. These are all interesting results from a waste recycling perspective.

2- The wood chips produced from wood waste type AI and AII by NSR were suitable for particle board manufacturing and comparable to those produced from fresh wood (wood chips from spruce). This is an important result from a sustainability perspective.

3- Using wood waste in the manufacturing of particleboard contributes to the development of commercial methods for recycling of the waste as a raw material instead using it just for energy recovery.

4- We have demonstrated for the first time the possibility of manufacturing a three-layered particle board based on wood waste material bonded by hybrid resin of TF and PMDI, where we succeeded in replacing PMDI as a fossil binder with 30% and 40% Tannin as a natural adhesive and the particle board still comply
with the European Standards EN 312 (2010). In this regard, an application for a worldwide patent has been filed and published. International Publication Number: WO 2019/117799 A1, see Annex 5.

5- Our innovative project RE:Source Project 42507-2 has demonstrated the possibility of manufacturing the following innovative variants of particle board from different types of wood waste, bonded by different green adhesive systems:

5-1. Three-layered Particle board bonded by a combination of TF-, PMDI hybrid resin: 30:70% or 40:60% (variants: V9, V10, V11) have physical and mechanical properties as well as extractable formaldehyde and formaldehyde release comply with the standards of EN 312 (2010) and fulfill the requirements of particle board type P1 (general purpose in dry conditions) and P2 (for interior fitments (including furniture) for use in dry conditions). Moreover, the thickness swelling value of particleboards variant no. 10 and no. 11 is better than the required value for Particle board type P4 specified by EN 312:2010 (Type P4: load-bearing boards for use in dry conditions).

5-2. Particleboard based on wood waste material (AI, AII) and bonded by animal’s albumin-protein resin (Innovative variants: V7, and V8) have achieved internal bond, modulus of elasticity, extractable formaldehyde and formaldehyde release comply with the European standard EN 312 (2010) and fulfill the requirements of particle board type P2 and P1 (bending strength). Moreover, the animal’s albumin-protein-resin bonded particleboard based on wood waste show very low values for formaldehyde release and extractable formaldehyde. So, can be considered as ultra-low formaldehyde release particleboard.

5-3. Three-layered Rape resin bonded particle boards from wood waste type AI, AII, AI+AII and SD+GW (variants:12, 13, 14 and 15), where variant no. 12 and variant no. 14 have achieved internal bond, modulus of elasticity, formaldehyde release and extractable formaldehyde comply with the European standard EN 312 (2010) and fulfill the requirements of particleboard type P2 (bending strength is close to fulfill the requirement of particleboard type P1). Moreover, the formaldehyde release and extractable formaldehyde of the manufactured variants (V12, V13, V14, V15) were superior, especially for the two variants V12, V15. Consequently, these variants can be considered as ultra-low formaldehyde emission particle board and variant no. 15 can be considered of special importance for construction, insulation purposes and to coat and decorate the inner walls of buildings.

6- We conclude that the amount of accumulated organic carbon in wood waste in Sweden is 0.7 million tons/year. If the particleboards were been manufactured
from the wood waste that is today incinerated it could contribute to a decrease in carbon dioxide emission in Sweden with some 0.5 million tons, which is equivalent to almost 1% of the total Swedish emissions of greenhouse gases. This would contribute to achieve the national goal on reduction of carbon dioxide emissions.

7- The major conclusion from this innovative project is that we have demonstrated for the first time the possibility of manufacturing innovative variants of particle board from different types of wood waste, bonded by an adhesive system based on leftover cakes of rape oil in natural state (Variants 12, 13, 14 and 15) which suggests that it is completely feasible to launch spinoff-projects aiming to investigate the feasibility of developing a renewable adhesive system (green adhesive) based on protein isolated from left over cakes of rape oil for the manufacturing of wood based panels (wood composites) which could comply with the European standards. Moreover, the Technical report of Georg-August University of Göttingen recommended further research work to develop and optimize a new adhesive system for the manufacturing of particle board and other wood panels based on protein extracted from left over cakes of rape oil (Rape = canola) as well as recommended to launch spinoff-project aiming to establish such an innovative canola protein adhesive.

8- The results from preliminary investigation to extract protein from left over cakes of rape oil in a simple way reveal that it is definitely an advantage to extract protein from the left over cake of rape oil. Furthermore, the extractions process and the gluing process of the wood particles must be developed further and optimized. Therefore, further studies should be performed to obtain a better understanding of protein behavior and improve its performance as a binder for particleboard. So, we recommended further research work to develop and optimize a new adhesive system for the manufacturing of wood composites based on protein adhesive extracted from left over cakes of rape oil. A project should be launched to establish such an innovative rape-protein adhesive.

9- The innovative particle boards variants resulting from this project were considered interesting by furniture producing- and design companies as well as customers who see “non-toxic” environments as future niches”, for example in hospitals, schools, kindergarten, offices, etc. The ultra-low formaldehyde release and formaldehyde-free particleboards seem to be completely in line with their wishes. However, more research as well as product-tailored commercialization plans are needed before competitive products can be put on the market.

10- Some particle board-producing companies have expressed interest in our models. Also some adhesive companies have also shown interest in the adhesive systems used in the production of our variants. Some rape-oil producers have
shown great interest in finding a better use for the rapeseed leftover cakes, today partly treated just as a waste. This together opens the door for commercial investments in the near future.

11- A conclusion regarding recycling of wood waste is that at most construction sites there are favorable conditions for separation of recyclable wood, metals and hazardous waste from residual waste. On the other hand, it is normally difficult physically and logistically to handle more fractions separately, due to lack of space. During different phases of a project also other fractions could and should be handled separately, for example clean and/or contaminated soils from excavations, concrete/bricks during demolition, plastic, cardboard and other packaging materials at the final stage of the construction. But it is most likely always impossible to avoid a fraction also with residual/mixed waste, even though you try to minimize it. This fraction can be sorted and to some extent recycled together with other types of industrial waste at municipal or private waste management sites

Next step and Future work

- Further research is needed and recommended to develop and optimize formaldehyde-free adhesives from rapeseed press cake (green adhesive) for production of particleboard and wood-based panels. The Technical report of Georg-August University of Göttingen recommended further research to develop technology and establish such an innovative rape protein adhesive system.

- When a commercially viable green adhesive is at hand, as a possible result from the continued research, tests with the new adhesive should be performed together with particleboard manufacturers on the market.

- The strategies for sorting and collection of wood waste at construction sites can be further developed and the results from this project opens the possibility of launching an innovation project for developing this strategy.

- The suggested use of rapeseed press cake opens the door to launch new projects for innovative byproducts based on the rapeseed cake.

Project Communication

Presentation of the project externally

We have had the opportunity to present the project externally on several occasions, including:

- "Ekmandagarna", SPCI, Stockholm, 30 January, 2018
• RE;Source-dagen, Linköping, 17 April 2018
• Recycling-dagen, Helsingborg, 2017 and 2018
• Sustainable Business Hub, Malmö 23 May 2018.
• The Swedish Waste Management Association (Avfall Sverige), November 2018.
• Conference at the University of Göttingen “Conference on Environmental Protection in Wood Industry, Göttingen 22-23 November 2018 (5. Fachtagung Umweltschutz in der Holzwerkstoffindustrie).
• Project presentation at a high level. Visit at NSR by Her Royal Highness Crown Princess Victoria.

Published scientific articles

Some results of the trials carried out in the project were published in the German, scientific journal of Wood Technology” Holtztechnologie”


The project has also received attention from Universities and students in Architecture and Construction, for example in a master thesis at Chalmers School of Architecture, Department of Architecture and Civil Engineering 2019 “Tales of the revived”, Sandra Moberg and Josefin Eliasson, where the project is mentioned as a reference.

Articles in the press

A number of articles has been published regarding the project, both in daily newspapers and technical journals. Some examples, see below:

- **Avfall och Miljö nr 2, 2018**, Bättre byggnahmaterial med träavfall. (Better building materials with wood waste)

- **Helsingborgs stad (HD) 2019**. Mahmood Hameed gör guld av det du slänger

- **Building Supply SE. 2019** Träprofessor vill revolutionera spånplattor.
  [https://www.buildingsupply.se/article/view/653842/traprofessor_vill_revolutionera_spanplattan](https://www.buildingsupply.se/article/view/653842/traprofessor_vill_revolutionera_spanplattan)

- **Svensk Byggtidning, Björn Asplind, 27 mars 2019**. Mahmood gör guld av det du slänger

- **NTT-Woodnet 27 mars 2019**. Kombinerar avfall för miljöns skull.
  [https://www.woodnet.se/](https://www.woodnet.se/)

- **Skog-supply.se 2019.**
The journal “Recycling” has awarded the project leader Dr Mahmood Hameed a place in the final round in the category “Innovator of the Year in Recycling” at the Recycling Gala, Stockholm, 2019 (Återvinningsgalan).

Contacts with potential stakeholders

During the project contacts have been established with a number of Swedish and German companies and other possible stake holders, including particleboard producers, adhesive producers, waste management companies, municipalities, construction companies, furniture producing- and design companies, rape oil producers as well as Universities.

Below is listed a number of companies and possible stakeholders, contacted within the project:

- IKEA Industry Hultsfred AB
- Byggelit AB
- Peab AB, Ängelholm
- MTA Bygg och Anläggning AB, Laholm
- SYSAV Utvecklings AB, Malmö
- Renova Miljö AB
- J G Andersson Söner AB, Linneryd
- Båstad Municipality
- Åstorp Municipality
- City of Helsingborg
- City of Lund
- Elka-Holzwerke GmbH, Morbach, Germany
- Pfeiferer Holzwerkstoffe GmbH, Neumarkt, Germany
- Georg-August University of Göttingen, Germany
- Université Pierre et Marie CURIE
- University of Lund
- Paperpals AB
- Huntsman, Germany, adhesive company
- Green Furniture Concept AB
- Zenit design AB
- Gunnarshögs jordbruk AB
- Kinnarps AB
- Skanska Sverige
- The WOODREGION, European innovative center
- Kronspan (Silva)
- Business Sweden
- Sven Norups Gård AB
- Riksbyggen huvudkontor i Stockholm
- One reality AB
- Tetra Park Packaging Solution AB
These contacts are most valuable and will be further developed in future projects, aiming at a commercialisation of the research results.

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References


- Al-Shekh F. 2013. Practical study of the importance of planting some strategy crops in saving carbon and mitigation the greenhouse effect phenomenon. Dissertation at New Life University Online for Human Development, Faculty of Environmental Development (www.su2233.com).


- Hameed, M., C. Behn, E. Roffael and B. Dix 2005: wettability of fresh chips (chips obtained directly from wood) and chips obtained by mechanical disintegration (M-chips) and thermohydrolytical degredation (T-chips) of particleboards with UF-, PF-resins and binders based on PMDI (polymers of diphenylmethan diisocyanates). European Journal of Wood & Wood Products 63: 394-395.


- UNFCCC, 1992. The United Nations Framework Convention on Climate Change is an international environmental treaty that was opened for signature at the Earth Summit held in Rio de Janeiro in 1992 and came into force in 1994.


Electronic websites:


Annexes

1. Administrativ bilaga (in Swedish),