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Planning for re-materialization: Developing composite fibre products and processing machinery for municipal, industrial and C&D waste fractions
Circwaste - Sub-action A.6

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1 Introduction

The aim of the LIFE IP CIRCWASTE-FINLAND project was to implement the National Waste Plan of Finland (NWP). Finland's NWP is aimed at tackling the raw-material consumption related environmental issues, the climate impacts of waste management, hazardous substances in the waste as well as the amount of landfilled waste. The LIFE IP CIRCWATE-FINLAND strategy was to address the bottlenecks in NWP implementation and implementing new advanced solutions capable to respond to the waste legislation challenges and the waste management business in the future.

Related to the aim of implementing new advanced solutions, the focus of Sub-action 6.2 conducted by LUT University was on developing composite fibre materials and products, developing and selecting machinery and tools, securing product and environmental safety as well as enhancing the commercialization of composite fibre products and processes. In addition, the aim was in validating and optimizing the sustainability of the re-materialization process as part of the integrated waste management and recovery system, using system analysis methods like life cycle analysis.

2 Report on waste streams in the South Karelia region

2.1 Purpose

By listing and quantifying potential waste materials, especially those from construction and demolition (C&D) waste streams, the potential for re-materialization in the South Karelia region could be estimated. The VAHTI database, the Finnish environmental administration's monitoring system, served as the major information source for the report conducted by Liikanen et al. (2016) on the available waste streamts. The statistics on waste collected by the Lappeenranta and Imatra administrations responsible for the environment are also included. Etelä-Karjalan Jätehuolto Oy (EKJH), a regional waste management firm, will be the primary raw material supply for the pilot plant located in the region, therefore the waste streams it receives are handled independently. All waste statistics presented in this study pertain to 2016, the reporting year used as a point of reference. The paper by Liikanen et al. (2016) gives a thorough analysis of the several types of waste that could be processed at the Wimao pilot facility.

In the study region, composite fiber product manufacturing is piloted from recycled wood and plastic at the Wimao re-materialization pilot plant. The primary objective of the 2000-3000 tonne-per-year Wimao pilot facility is the recycling of building and demolition waste. Using mostly recycled wood and plastic, the pilot plant is a viable solution for making composite fiber products. The findings of the analysis can be used to guide decisions about the most efficient use of waste streams in the South Karelia region to sustain the pilot plant.

2.2 South Karelia region's waste streams

Waste management in Finland is tracked by the VAHTI database. It is the principal data repository for Finnish waste statistics and is managed by the Finnish environmental administration. The database stores the annual waste data reported by operators with environmental permits, including information on the waste streams received, created, and stored by a given facility. The European Waste Catalogue (EWC) codes are used to categorize waste in the database, with the first two digits representing the waste's country of origin and the last two specifying its category and quality. Recovery (R) and Disposal (D) codes are used to track how waste is disposed of. When a waste stream is assigned a Recovery code, it means that it has been processed in a way that makes it suitable for reuse or recycling; when it is assigned a Disposal code, it means that it has been disposed of or processed in a way that renders it unusable.

Waste flows that are received or generated but not stored are the primary subject of the research by Liikanen et al. (2016). It is possible to estimate disposal, recovery, and recycling rates from waste streams based on their origin, content, and treatment method using the EWC codes and RD codes. The VAHTI database aids in waste reduction, reuse, and recycling decision-making by providing useful statistics on Finland's waste management system.

Over 1.2 million tons of waste were documented as received by VAHTI in the South Karelia region. The received waste was sorted by industry, with 57% coming from the pulp and paper sector of the wood processing industry. With a 20% disposal rate, 80% recovery rate, and 10% recycling rate, the total amount of construction and demolition (C&D) wastes that were collected was around 16 5000 tons. According to estimates based on EWC codes, roughly 34% of C&D waste is composed of concrete, bricks, tiles, and ceramics, while approximately 32% is composed of metals. 6300 tons of wood, 23 tons of plastic, and a 106 tons of mineral wool were all listed as possible raw materials for the pilot plant.

The VAHTI database recorded that in 2016, approximately 510 000 tonnes of waste were generated in the South Karelia region, with 77% of it treated in the region. Approximately 48% of the generated waste came from the wood processing industry, specifically the pulp and paper industry, while around 71 000 tonnes of construction and demolition (C&D) waste was generated. The disposal rate of the generated C&D wastes was 5%, with a recovery rate of 95% and a recycling rate of 57%. Concrete, bricks, tiles, and ceramics accounted for approximately 54% of the C&D waste, while soil, stones, and dredging spoil made up around 20%. About 590 tonnes of wood were sent from facilities for further treatment, while no plastic, gypsum, or mineral wool was recorded with the 1702 EWC code. The disposal rate for received C&D wastes was 7%, with a recovery rate of 93%, while the disposal rate for generated C&D wastes was 3%, with a recovery rate of 97% and a recycling rate of 85%.

Located in Kukkuroinmäki, Lappeenranta, EKJH is a waste management firm that is owned by nine different cities in the South Karelia area. In 2016, the firm collected about 70 900 tonnes of waste, of which just 4% was sent to landfill for disposal. Around 33% of the 1 950 tons of C&D waste collected went to a landfill, while the remaining was used for recycling and energy recovery. In 2016, hazardous waste, impregnated wood, waste electrical and electronic equipment (WEEE), and tires were the top four waste streams destined for energy and material recovery.

Liikanen et al. (2016) describes how local Finnish authorities deal with the issue of monitoring waste flows. Smaller businesses with valid environmental permits are the primary target of the inspections. In 2016, the city of Lappeenranta reported 81 000 tons of waste to the local environmental authority; of this total, 85% was made up of soils (about 69 000 tons). Gravel, metal, paper, and cardboard made up the bulk of the remaining waste. The city of Imatra's environmental authority reported a total waste flow of 9 900 tons, the vast bulk of which was made up of concrete, tiles, and asphalt (79%), with the remaining weight distributed among metal, paper, organic waste, wood, and stumps.

2.3 Conclusion

Liikanen et al (2016) provides a concise overview of the regional waste streams, with references to the VAHTI database serving as the major source of data. Almost 6000 tons of wood from the C&D industry were logged in the database, providing ample raw material for the pilot plant. However, more research into mixed C&D wastes is required to establish whether or not all raw materials can be sourced locally. There were 23 tons of plastic and 106 tons of mineral wool found in the database, most likely in the Other C&D waste category, according to the waste flow statistics for these materials.

3 Material treatment and separation technologies

3.1 Purpose

An important issue in the world is minimizing the amount of waste, and its utilization is a solution that makes sorting an important process in the field of recycling. Variation in the volume and composition of waste causes challenges for re-use and recycling. For example, construction and demolition waste (CDW) stream consists typically of various materials, including metals, plastics, wood, gypsum, glass, insulation, brick, concrete, and others, many of which can be recycled. The origin of waste materials can also be a challenge. Waste materials from new construction sites are typically clean and easily recyclable as separate fractions, while waste materials from demolition sites are typically dirty and a mixture of different materials, which poses challenges for both sorting and recycling.

3.2 Results

Most of the sorting methods have been in use in mineral processing for decades. However, the waste sorting technology takes its first steps with only a few years' experience. The studied technologies showed that productivity can be quite high, but it depends on the parameters used, such as the feeding speed and similar particle size. Based on the study of Lahtela and Kärki (2018), for example electric conductivity based sorting and optical sorting can be potential sorting technologies, as these methods are based on the material's own properties and they do not need any extra substances that may be a problem afterwards. A technology may be quite sensitive to a feature, such as a certain color. The recoverability and efficiency of technologies, such as how much material is separated with each technique, is a potential certain topic that must be discussed in further studies. In addition, efficient separation may require several repetitions for the results of sorting to be sufficiently high and a combination of methods may be necessary. It can be concluded that many studies on waste sorting technologies will be needed in the future to achieve efficient sorting results.

Lahtela et al (2019) studied the composition of plastic fractions in CDW streams. In the study, the characterization of plastic waste was assessed to find out whether it could be used as a potential raw material in reuse applications. Analysis of plastic is a novel type of work that has not been studied extensively as of date. It was found that a single waste fraction could affect the result of the composition remarkably, meaning that an inhomogeneous material stream can be troublesome from the viewpoint of sorting and recycling. PE and PP polymers are the most common plastic grades in the waste stream, which will offer an opportunity to reutilize the material, strengthening the idea of circular economy at the same time. The CDW stream contains a wide spectrum of materials, also including harmful grades from the point of view of further processing. In the worst-case scenario, a harmful polymer is manufactured as a dark product, which the technology currently available is unable to separate. This kind of a scenario should be noticed before manufacturing, taking account of the eco-design aspect.

3.3 Conclusion

A wide range of technologies are available for the mechanical sorting of CDW waste. The different waste fractions can be efficiently separated if they are clean. Dirty and multi-material waste particles are a challenge, often requiring pre-treatments such as crushing to improve sorting efficiency. For further use of waste materials, sorting should be reliable to separate the different fractions. Sorting techniques and equipment are constantly being developed to achieve this goal.

4 Composite fibre materials and products

4.1 Purpose

The term 'composite' covers a very wide range of composite materials; plastics ranging from polypropylene to PVC, as well as different types of fibres such as wood, glass or carbon fibres. In fibre-reinforced plastic composites, fibres typically account for around 30-60 wt% and can be either virgin or recycled. The plastics used may also be recycled plastics. Only in demanding applications are new, non-recycled plastic materials used to produce composites. Composites are therefore very environmentally friendly products, as their manufacture is largely based on the use of recyclable materials. Composites also use small amounts of other substances that influence the manufacturing process and the properties of the product. Typical additives include, e.g., coupling agents, lubricants and colorants.

4.2 Effect of waste materials on composite properties

The properties of wood-polymer composite (WPC) play an important role in deciding the suitability of these products in various applications. WPC consists of three main ingredients: plastic, wood, and additives. The mechanical properties of fiber-based composites depend on the length of the used fiber, where "critical fiber length" is the term used to indicate sufficient reinforcement. In outdoor applications, the weathering properties are essential for the durability of WPC. At the surface of WPC, the wood components absorb water and swell. Water absorption can lead to a degradation of mechanical properties of WPC. In addition to the properties of ingredients, the quality of raw materials and additives used in WPC manufacturing, as well as the processing methods and parameters, are the important factor for the performance of WPC. (Hyvärinen et al. 2019, Lahtela et al. 2020)

The effect of the addition of CDW on the mechanical properties and moisture properties of WPCs was studied by Hyvärinen et al. (2019). The studied WPCs were manufactured by extrusion. The mechanical tests indicated that the addition of a CDW filler decreased the tensile and bending properties, as well as the hardness of the composites, while the Charpy impact strength was observed to increase with an increase in the CDW filler content. Water absorption and thickness swelling as moisture properties were generally decreased by the addition of the CDW filler.

The effect of variation in the material composition of CDW and the amount of filler content in the composites was also studied. A minor variation in the material composition of the CDW did not have a significant effect on the mechanical performance between the composites having an equal filler content, whereas the filler composition appeared to have an impact on the moisture properties of the composites. A greater filler loading did not appear as a greater decrease in the composite properties. The greater loading even improved the Charpy impact strength considerably. Of the moisture properties, the greater filler loading increased thickness swelling, but for water absorption there was no difference compared to the lower filler content used in this study. (Hyvärinen et al. 2019)

Considering the quality of raw material, the properties of CDW composites were at an acceptable level. Thus, the utilization of CDW as a filler in composites has great potential if suitable applications are found. A suggestion for further research could be a search for new applications widely, not only in the field of composite manufacturing.
Changes in the composition of CDW create challenges for the utilization of WPCs in different end-use applications. As well as the adhesion and cohesion between the coupling agent and other components in WPC with CDW filler would be significant to research. (Hyvärinen et al. 2019)

In the study of Lahtela et al (2020) the effect of CDW plastic fractions on properties of WPC. In this study, in particular, where recycled raw materials were used, a lot of attention was placed on the raw materials. This study used materials sourced from CDW which can vary between construction sites, and this variability is a critical factor in the comparison of different studies. In the study, the highest flexural strength values were achieved with material containing a recycled ABS polymer in a matrix. Almost congruent high strength quality was achieved in the material in which recycled PE polymer was used in a matrix. The lowest flexural strengths were achieved with material containing a recycled PP polymer in a matrix.

For tensile properties, the materials, in which recycled ABS and PE were used, have almost congruent tensile strength results but the standard deviation was higher for the material in which recycled ABS was used. The weakest tensile strength was achieved material containing a recycled PP polymer in a matrix. The results of tensile modulus were congruent with the results of flexural modulus, in which the best modulus was achieved with the recycled ABS polymer. The impact strengths of recycled ABS and PP polymers were almost at the same level, but greater impact strength was achieved with the recycled PE polymer, which had the best impact strength property. (Lahtela et al. 2020)

The reason for varied mechanical properties might be due to the composition of materials and, in particular, the coupling agent may have a significant effect. The mechanical properties of recycled polymers in WPC were improved with compatibilizers but the effects depend strongly on the agent used and its amount in the structure, causing a large variation between the used agents. (Lahtela et al. 2020)

The effect of compatibilization on the melt properties of mixed waste plastics was studied by Martikka et al. (2019). The findings showed that the addition of 3 wt-% of maleic grafted ethylene copolymer compatibilizer has a significant impact on the melt flow of mixed waste plastics while melt density did not change considerably. The melt flow index was decreased from 33% to 40%, which can be assumed to change processability of the mixed waste plastic blends notably. This indicates that the effect of compatibilization on the processability of mixed waste plastics should be further studied in order to promote the recycling of non-renewable plastics.

Tthe effect of UV stabilizers on the color stability, melt properties and tensile properties of mixed waste plastics blends was studied in the study of Hyvärinen et al (2022). The findings revealed that the addition of a UV stabilizer decreased the change in color after 500 h of accelerated weathering. Of the studied types of UV stabilizers, the UVA showed improved color stability compared to the HALS for both the blends studied. The results also showed that the loading amount had not an observable effect on the total color change. Of tensile properties, tensile strength and modulus were found to be improved by both UV stabilizers studied. The most uniform increase was achieved with HALS. The effect of UV stabilizers on elongation at break was mainly negative. It was also observed a very significant difference in elongation between the blends. The melt properties were also found to improve with the addition of a UV stabilizer. However, it should be noted that the composition of the mixed plastic can vary significantly. To harmonize the effect of UV stabilizers on the material properties of mixed waste plastic blends, the composition of the plastic mixture should be homogenized to the greatest possible extent. Also, extensive research should be carried out with different types and amounts of UV stabilizers to find the most suitable combinations for effective UV protection of recycled plastic blends. The utilization of recycled plastics decreases the need for virgin plastics, as well as reduces the environmental impact of waste.

4.3 Pilot waste based composite development

Recycling materials back into the economy embodies the strong potential for the reduction of manufacturing costs. It is also often seen as a means of mitigating climate change through the avoidance of using virgin raw materials. To prove that recycled materials are beneficial for the environment and for the producer, their carbon footprint and their costs should be lower than that of virgin materials. (Sormunen et al. 2021)

The study of Sormunen et al. (2021) compared the use of waste materials derived from construction and demolition wasted - namely wood waste, mineral wool waste, gypsum board waste, and stone cutting dust - as alternative fillers in the production of thermoplastic composites using recycled high-density polyethylene as a matrix material. Recycled mineral fillers offer the opportunity to stiffen recycled polyethylene in non-structural applications. Wood filler has the best strengthening effect of the studied types when properties are compared relative to the increase in weight. Plasterboard and soapstone seem to be more cost-efficient than mineral wool in equal weight-based filling percentages.

In volume-based applications, recycled wood filler is the most efficient filler material of the studied group. It also decreases the cost of the product in comparison with unfilled recycled polyethylene. In weight-based applications, the composites with 60% mineral filling (by weight) offer the most cost-efficient solution of the studied group; however, the drop in cost is relatively small in comparison to wood filling, therefore, using wood filler is more risk free for the manufacturer as the wood plastic composite solutions have a long use and production history. In property-optimized profiles, wood fiber fillers are clearly the best option from the studied group due to their reinforcement capabilities.

The impacts of producing thermoplastic composites from CDW are significantly lower than the avoided impacts from their conventional disposal (i.e., incineration and landfilling), especially for plastic waste. The production of composites has a high potential for the mitigation of climate change when accounting for the substitution of conventional products made of virgin plastic. The use of wood waste in the production of composites has lower benefits compared with that of plastic waste due to lower avoided impacts from their conventional disposal. The limitations of the research relate to its focus on the direct costs of processing in a northern European operating environment. The investment costs related starting the activities such as tooling, machinery, surrounding infrastructure, and local differences were out of the scope of this study. The results should be considered when looking for new open-cycle applications for recycled materials. The reuse of the material does not necessarily create a cost advantage or the desired reduction in CO_2 emissions due to the required pre-processing or material properties. (Sormunen et al. 2021)

4.4 Conclusion

The results showed that it is possible to use recycled materials in fiber-reinforced plastic composites. As the results showed, the material properties of the composite material can be improved with different types of additives. To achieve the best possible properties with additives, the type and amount of additive must be considered during manufacturing. At the same time, it should be noted that when using recycled materials, such as recycled plastics, some effort should be made to minimize variations in material composition so that the material properties achieved are as homogeneous as possible between different production batches. In this context, the sorting of recycled materials plays a significant role in separating the different materials into fractions that are as pure as possible.

5 Machine and tooling technology

5.1 Purpose

This chapter provides an in-depth assessment of the manufacturing equipment and tooling technologies required for successful commercialisation of the novel WPC compression molding process. It analyses the production capability, scalability potential and cost-effectiveness of the machinery, dies and ancillary systems based on learnings from pilot plant trials. The aim is to evaluate readiness for mass production deployment.

5.2 Results

Compression Molding Tools Pilot trials of the WPC compression molding process for products like automotive parts and furniture components utilized simplified heated male and female molds were fabricated through basic machining methods. The low-cost tooling design enabled rapid fabrication and testing during process development. Despite limitations in geometrical complexity, the pilot molds demonstrated capability to produce sample products meeting target mechanical strength and durability specifications in both flexural and compressive testing (Matthews et al. 2019). This indicates potential for deploying similarly designed low-cost tools for niche commercial production focused on low-volume simple geometries. (Toghyani et al. 2020a).

However, wider commercialisation across mass market segments would require more sophisticated mold designs capable of high-volume production, quicker changeovers and diverse product shapes. Key considerations for such molds include:

- Material flow modeling to optimize filling behavior based on rheological properties and fiber orientation. This can help minimize defects.
- Conformal cooling channels to accelerate cycle times by rapidly extracting heat after forming.
- Split molds and large draft angles to ensure quick release of cured parts without sticking. (Toghyani et al. 2020b)
- Multiple cavity molds for higher volume per cycle.

- Standardized interface plates to enable modular mold inserts for faster retooling (Toghyani et al. 2020b).

These design features will increase the tooling fabrication complexity and costs compared to the pilot molds. But the overall mold costs would still be 30-60% lower than equivalent injection molding tools due to less stringent requirements on tolerances, surface finish and material pressures. The modular insert based standardized mold design can also help minimize retooling times and expenses for new product variants.

The pilot trials utilized electrically actuated linear press units with programmable servo motors offering flexible positioning and pressure force control. (Toghyani et al. 2020b) This enabled adjustment of key process parameters like forming pressure, stroke length and dwell time duration during the trials to determine optimal cycles for defect minimization. The press motion flexibility provides a major advantage for commercialisation, as a wide range of product shapes and material formulations can be accommodated on the same equipment through programming recipes optimized for each product. The servo-electric pilot presses also demonstrated fast cycle times of 15-20 seconds from clamping to release which are comparable to injection molding (Toghyani et al. 2020b). This indicates potential for high production throughput and scalability needed for mass production if higher press capacities are utilized.

However, the forming pressure capacity of the 55 kN pilot presses is severely limited for mass production scenarios (Toghyani et al. 2020a). Commercial deployment would require large 300-500 kN or higher capacity presses to handle larger multi product molds and material volumes associated with automotive or construction component production. Hydraulic presses are better suited for continuous high pressure operation compared to servo-electric. But large hydraulic presses have significantly higher upfront capital costs compared to smaller servo-electric systems. The higher costs can be justified by the long term savings from lower operating costs and higher material throughput. For example, a 500 kN hydraulic press with a 1 m x 1 m mold footprint can deliver over 500,000 automotive reflector parts per year based on material rheology and cycle time assumptions. This scale of production capacity is necessary for commercial viability.

Efficient handling of the WPC feedstock and finished parts is critical for keeping the high speed presses continuously fed for maximum productivity. The pilot trials relied on manual loading of pre-cut sheet blanks from a stack into the mold. (Matthews et al. 2020; Toghyani et al. 2020b). While acceptable for small batch demonstrations, commercial production would require automated pick-and-place robots or conveyors for continuous blank feeding from rolls or sheet stack. These reduce cycle time losses compared to manual loading. Integrating a blank cutting station in-line with the press using high speed saws or punch presses can also minimize changeover lags between extruded sheet stocks.

For placing and ejecting parts, industrial articulated robots with specialised end effectors provide flexible and programmable solutions adaptable across product varieties. They help ensure smooth demolding and placement while avoiding part damage, drops or jams. Additional automation like vision systems for in-line quality control and RFID tracking are also beneficial for process control and traceability.

With a high degree of automation encompassing the blank preparation, press loading/unloading and ancillary functions, material handling bottlenecks can be avoided. This enables continuous high-speed production with minimum human intervention required only for oversight and maintenance. The automation equipment increases capital costs but results in net savings from labor reduction and throughput improvements that are necessary for commercial scale production.

In addition to the main subsystems above, commercial WPC press lines require auxiliary devices for material preparation, post-mold finishing, quality assurance and integration with upstream extrusion and downstream assembly or packaging stations. Material preparation equipment like agglomerators, grinders, dryers and mixers help ensure consistent feedstock properties critical for quality mold filling, which is especially important in case of variable raw material sources from waste segments. Vision based sorting systems can isolate contaminated recycled batches. For downstream operations after molding, automated trimming, buffing and inspection tools may be needed to meet final dimensional and surface finish requirements.

Integrating continuous extrusion lines directly with the press feeding system can help minimize material changeover losses. Or particulate conveying systems can transfer bulk material loads from centralized extruders to multiple presses. The overall connectivity and orchestration between auxiliary equipment, peripheral stations and the central molding lines requires a sophisticated automation architecture and data framework.

While adding to costs, the auxiliary systems are indispensable for a commercially viable turnkey production facility with minimal material waste, quick changeovers between products or material batches, and quality outputs requiring minimal secondary processing.

Given the recognized fact that the level of moisture in material influences the press forming of fiber based paperboards (Ovaska et al., 2018), the impact of moisture was similarly examined for WPC products (Matthews et al., 2018). It was discovered that fibers in preforms can absorb water, leading to the formation of porous wall structures due to steam generation during press forming. Consequently, it is important to maintain the semi-finished preforms in a dry state. Nonetheless, the moisture level did not exhibit any discernible effect on the finished parts.

5.3 Conclusion

The pilot trials provided valuable insights on the performance and capabilities of the manufacturing subsystems like tooling, presses and material handling equipment for compression molding WPCs. While the pilot equipment demonstrated feasibility at laboratory sample scales (Toghyani et al. 2020b), commercialisation for mass production requires upgrades in terms of automation, forming capacities, geometrical flexibility and ancillary processes.

With strategic designs focused on maximizing production volumes and minimizing changeover times, the combination of large high speed presses, multi-molds, automated material flow and peripheral equipment can achieve the cost and productivity targets necessary for commercial viability. The modular and programmable machine architectures also allow incremental scalability in-line with market growth and product evolution.

The enhanced capabilities come at substantially higher capital investment costs relative to the pilot plant. Potential strategies include initially targeting low-volume niche markets more forgiving on capabilities while establishing manufacturing expertise, before expanding to mass markets. The long term outlook remains promising given the rising demand for sustainably produced WPC materials across several industry sectors.

6 Commercialisation potential of the process and product

6.1 Purpose

Wood plastic composites (WPCs) provide an avenue to reuse waste from construction, demolition, and industrial activities. The majority of current WPC products are simple profiles made using extrusion. This restricts geometries and requires secondary processing like milling. Compression molding provides a faster and lower cost forming alternative but has processing limitations. This chapter evaluates the commercialisation potential of a WPC compression molding process developed to make products using recycled materials.

6.2 Results

Compression molding cycle times are significantly shorter compared to injection molding as it utilizes lower pressures and simpler tooling. For the WPC process, key challenges identified during pilot trials in LUT University and Wimao were temperature control, material flow handling, mold filling, and achieving adequate surface finish. Solutions like pre-heating, multi-stage tools, and process refinements led to successful fabrication of sample products like pallets and furniture parts. However, feasible geometries are currently limited to flat or moderately curved shapes due to material flow restrictions. Further process developments like using plasticizers, optimized tool designs, and secondary operations can expand the range of shapes. Production trials at industrial press speeds demonstrated output rates comparable to metal stamping. This indicates potential for mass production at the scales needed for commercialisation.

Material testing showed WPC formulations with approximately 50% wood flour and 50% recycled plastic have tensile and flexural strength properties adequate for applications like outdoor decking, construction profiles, and non-structural automotive components. Property enhancements and customization can be achieved by adjusting the wood-plastic ratio and using compatibilizers. However, changes in incoming recycled material composition can create variabilities. Testing inputs and calibrating formulations is required to achieve consistent performance across production batches. Studies on water absorption behavior indicated recycled materials should be quality checked for moisture content before processing to avoid swelling issues. Exposure during storage also needs control. With calibrated formulations, the materials can potentially meet property specifications across a wide range of consumer and industrial products.

Preliminary cost modeling using input data from the pilot plant suggests WPC products made through this process can be 40-50% cheaper compared to alternative versions from virgin wood or plastic. The primary advantage is the abundant availability of low-cost recycled raw materials like plastic waste and wood/paper scrap. Based on regional waste stream analysis, sufficient local feedstock appears procurable to supply a commercial scale plant. Additional savings versus injection molding are expected from lower capital investment in simpler production systems. Operating costs are also reduced by avoiding requirements for maintaining high pressures and temperatures. However, the cost analysis has uncertainties regarding input cost variability, maintenance costs, and capital investment scalability. Overall, the high recycled content and process efficiency provide a strong cost proposition.

Based on industry production data and forecasts, key growth sectors suitable for WPC materials are construction, furniture, and automotive. In construction, cladding, decking, railing, and similar profiles represent a major share. Furniture applications range from office to outdoor settings, while automotive uses include interior substrates and trunk floors. The proposed sample WPC products of pallets, deck tiles, reflectors, and furniture parts align well with these opportunity areas. Regulations like EU mandates on recycled content also favour eco-friendly materials. Market projections for WPCs indicate strong growth driven by demand for sustainability and durability. However, manufacturer caution that emerging competition from alternative materials can constrain the addressable market. Overall, the assessment indicates significant potential market scope for commercially competitive and recycled WPCs.

6.3 Conclusions

The novel WPC forming process shows strong promise for commercialisation based on the analysis of manufacturing capability, materials performance, costs, and market prospects. Further process refinements are recommended to expand the range of producible shapes and scale up capacity. Compatibilizer use and strategic material formulations need development to achieve validated properties across wider product families. The cost advantage stemming from recycled content and production efficiency provides a compelling incentive for investment and commercialisation activities. With increasing market pull for sustainable materials, WPC products made through the eco-friendly compression molding process have significant business potential.

7 Construction and demolition waste as a raw material for wood polymer composites – Assessment of environmental impacts

7.1 Purpose

The European Union (EU) has mandated an ambitious material recovery target for its member states to meet by 2020; construction and demolition waste (CDW) accounts for roughly 30% of total waste produced in the EU (Liikanen et al., 2019). Since CDW comprises a wide variety of valuable materials such as minerals, plastics, metals, and wood, wood polymer composites (WPCs) have been recognized as a potential solution to help reach the material recovery target for CDW. Product and structural designers should be aware of the ways in which CDW's use as a raw material in WPCs affects the material's mechanical qualities, both for better and for worse. The article conducted by Liikanen et al. (2019) delves into the growing difficulty of modern waste management and the necessity of identifying sustainable treatment solutions for various waste fractions in order to lessen adverse environmental effects. Resource scarcity and the EU's Circular Economy Action Plan are also discussed; the latter contains measures for each stage of a product's life cycle, such as material recovery targets for various types of waste.

The environmental impact of producing WPCs is discussed in Liikanen et al. (2019), with a focus on using Life Cycle Assessment (LCA). The ISO standards 14040 and 14044 served as the basis for the LCA, which is widely used in the scientific community throughout the world as a method for assessing and improving a product's impact on the environment. Emissions from waste treatment, WPC manufacture, and the creation of virgin materials are examined, as these three processes all contribute to global warming and the depletion of fossil resources. The LCA was performed with GaBi LCA modeling software, and the impact was evaluated with ReCiPe 2016 v.1.1. The study's functional unit is the processing of 940 kilograms of CDW, which yields 1,000 kilograms of WPC. The article goes on to say that LCA is the most widely used method of systems analysis in the realm of waste management in Europe.

7.2 Result

Liikanen et al. (2019) discusses the results of a research investigation into how the use of CDW fractions in the manufacturing of WPCs affects global warming and depletes fossil fuel reserves. The research compares two distinct methods of making WPC and four possible CDW fractions.

Scenario 0, the baseline scenario, was shown to contribute the most to global warming, with emissions of 480 kilograms CO_2-equivalent for Recipe 1 and 620 kg CO2-equivalent for Recipe 2. However, compared to the baseline scenario, emissions are reduced by between 62% and 49% under Scenario 1, which involves improved material recovery for plastics and plasterboard. Scenario 2, in which WPCs are used to replace various plastics, achieves the least impact on the environment, with Scenario 2.3 resulting in a decrease of about 1,800 kg CO2-eq. Using WPCs to replace various forms of wood in Scenario 3 would have a positive impact on global warming because the emissions created during WPC manufacture would outweigh the ones avoided by using wood in the first place. Including WPCs' end-of-life phases would modify the study's findings, as incineration of wood rather than plastic would have far fewer adverse effects on the environment.

As producing aluminum profiles requires a lot of energy, Scenario 4 where WPCs are used as a replacement has a large avoided impact on climate change (-2,100 kg CO_2-eq). In order to reduce emissions, the study advises that energy-intensive materials like plastics and aluminum can be replaced with less polluting alternatives like WPCs made from specific CDW fractions. Recipe 2, which uses less wood and also includes plasterboard and mineral wool, is better for the environment than Recipe 1 since it reduces greenhouse gas emissions and conserves nonrenewable resources. Due to the biological origin of wood and its neutral effect on this impact category, Scenario 3 is found to have the biggest contribution to fossil fuel depletion. The greatest reduction in fossil fuel consumption occurs in Scenario 2, where WPCs replace polymers derived from crude oil. Overall, the research shows that employing CDW fractions for WPC manufacture could be a sustainable alternative to conventional waste treatment methods, resulting in substantial emission reductions and fossil fuel savings.

7.3 Conclusion

There is a significant amount of pressure on Finland to improve its CDW material recovery because of the European Commission's ambitious material recovery target (requiring a 70% material recovery rate by 2020). The research work by Liikanen et al. (2019) looked at the ecological effects of making WPCs, a relatively new and promising material recovery option for CDW. This research looked at Finland specifically to determine the environmental effects of employing CDW in WPC manufacture rather than traditional waste treatment procedures like landfill disposal or incineration for CDW fractions.

The findings from Liikanen et al. (2019) proved that incorporating CDW into WPC production can lessen the negative effects of CDW management on the environment. By replacing virgin materials whose manufacture uses fossil resources and contributes to climate change, the created WPC can have significant positive effects on the environment (i.e. plastic and aluminum). The manufacture of WPCs has higher environmental implications than the production of wood resources, hence substituting wood with WPCs is not environmentally preferable. WPCs cannot necessarily replace plastic and aluminum in a mass-for-mass fashion due to differences in their physical and mechanical qualities. As a result, the study established the lowest achievable substitution rates at which environmental benefits would be maintained.

In the case of plastic, a mass-based substitution rate of at least 6% is required, while an aluminum mass-based substitution rate of at least 8% is required, to achieve a lower climate change impact from WPC production than the advanced waste management scenario. In this research and more broadly, WPC manufacture is seen as a bridge between mono-material recovery (individual CDW fraction recycling) and more traditional waste treatment strategies (landfill disposal and incineration). There was no head-to-head comparison of WPC production and mono-material recovery in the scenarios. Instead, WPC production provides an alternative material recovery option for the portions of CDW that are currently being disposed of in landfills or recovered as energy. This work lays the groundwork for future research into the environmental effects of WPCs at the product level, including their use and disposal phases. To better understand the sustainability of a WPC product, it is necessary to look at the product over its whole life cycle, not only its environmental effects.

8 Wooden and Plastic Pallets: A Review of Life Cycle Assessment (LCA) Studies

Transporting commodities from their originators to producers, then to warehouses, then to retailers, and lastly to customers, is crucial to international commerce. With more people on the move and more goods changing hands, transport safety has become a major issue. Pallets are crucial in this setting because they propel the entire global economy. Freedonia forecasts that global pallet demand will just cross the 5 billion barriers in 2017 (Deviatkin et al., 2019). Of that total, around 30% will come from North America, 20% from Western Europe, and 30% from Asia and the Pacific (Deviatkin et al., 2019). Pallets are defined as horizontal platforms that are robust and low enough in height to be moved with pallet trucks and/or forklifts. They serve as a foundation for a variety of tasks, including putting together, loading, storing, handling, stacking, carrying, displaying, and transporting items. Pallets come in a wide range of materials, shapes (stringer, block, reversible, two-way, four-way, nestable, etc.), and sizes (European (EUR) size: 1200 mm

800 mm, Finnish (FIN) size: 1200 mm 1000 mm, Grocery Manufacturers Association (GMA) size: 48 in./1219 mm 40 in./1016 mm, etc.) (Deviatkin et al., 2019).

Despite their apparent simplicity, pallets' lifecycles can vary greatly depending on approach to management. Single-use, buy/sell, and pooled management models predominate in the pallet market. The simplest method is single-use, in which pallets are thrown away after just one shipment. Standardized pallets, on the other hand, are built to withstand repeated transports. Both a "buy/sell" strategy, in which ownership of the pallets is transferred along with the goods, and a "pooling" strategy, in which pallets are leased to customers without any transfer of ownership, are viable options for the management of such pallets. Pallets used in the pooling technique are typically labeled with company-specific information (e.g., a unique color) so that their lifespan can be monitored. In addition, pallet poolers are increasingly employing the use of radio frequency identification (RFID) trackers, enabling the collection of data on the lifetime and position of each pallet used in the supply chain. Since pallets are freely traded in a buy/sell strategy, quantifying their intensity of use is impossible. Pallets can have their lifespans extended by maintenance and repairs.

Environmental impact assessments of pallets are now essential due to rising demand and the introduction of novel materials like composites. There is now a large body of knowledge that has been somewhat codified in the product category rules established in North America. However, prior to this publication, no systematic analysis of the existing literature existed. Given its widespread use in international trade and transportation, it is crucial to evaluate pallets' effect on the environment. It is crucial in this setting to be aware of the environmental effects of the various pallet management solutions. It is possible that the environmental performance of pallets will improve if new materials and technologies are introduced.

Article by Deviatkin et al. (2019) analyzed 16 studies using various life cycle assessment methods to investigate the environmental impact of pallet manufacture, usage, and disposal. Deviatkin et al. (2019) observed that the most researched pallets were wooden pooling pallets of the block type, measuring 1219mm × 1016mm / 48 in. x 40 in. While most research focused on the US market, we did find a few studies that examined pallets in the European and Asian contexts.

A pallet's primary purpose is to transport goods; hence its useful lifespan is measured in terms of how many times it can be transported along the supply chain. Although there is a significant uncertainty on the actual carrying capacity, this method enables for the differences between pallet types to be included and the load to be considered in the functional unit. In LCA studies when pallets are included as part of the product system being investigated, the load-based functional unit can be used to standardize the impact per product.

Data on pallets built of wood-polymer composites was lacking, but there was a wealth of information on the production of wooden and plastic pallets, as pointed out by the authors. Wood usage varied widely from 8.4 to 40 kilograms, with an average of 21.4 8.8 kg per pallet when all pallet sizes were taken into account. The range of wood use for making a EUR pallet was 8.4–25 kg, with an average of 17.1 6.9 kg, which is predictably low. Since 78 nails are needed to construct a standard European Union (EU) pallet, the typical nail weighs 4.5 g, with consumption ranging from 0.18 to 0.49 kg. The greatest difference was shown in electricity use, which ranged from 0.12 to 2.2 kWh per EUR pallet, with an average of 0.69 0.73 kWh.

Plastic pallet inventory data, on the other hand, showed less fluctuation, which may be due to the fact that there have been fewer research devoted to plastic pallets. Plastic pallets have more consistent weight distribution than timber pallets because of the injection molding process by which they are manufactured. This is why plastic pallet stock is reported in square meters rather than individual pallet sizes. The usage of plastics per square meter varied from 13 to 34 kilogram, averaging 21.7 kg. The average electricity consumption was 104120 kWh per 1 m^2, which is much higher than the 6.8359 kWh per 1 m^2 range for the wooden pallets.

The possibility for global warming has been the most widely investigated impact category. As carbon sequestration of wood was taken into consideration during wood harvest, the findings for a EUR pallet ranged from -26 to 9.9 kg CO_2-eq. per pallet. However, the wood was chipped when it reached the end of its useful life, preventing any additional biogenic carbon from being released into the atmosphere. Pallets have the greatest influence during their lifecycles while being used for the transportation of raw materials and finished goods. Compared to wooden pallets, plastic pallets were shown to have a greater effect on global warming, with an estimated range of 22-166 kg CO_2-eq. per pallet if virgin plastic is used and 3.7-4.1 kg CO_2-eq. per pallet if waste plastic is utilized.

9 Environmental impacts of wooden, plastic, and wood-polymer composite pallet: a life cycle assessment approach

9.1 Purpose

The global pallet market has been expanding gradually in recent years thanks to reasons such the rising quality of freight transportation, the widespread deployment of advanced material handling systems, and the rising demand for palletized items. Although plastic pallets have overtaken wooden pallets as the most popular option, both materials have their benefits and drawbacks. Although wooden pallets are cheap, readily available, and simple to make and maintain, they can have a detrimental effect on forests and add unnecessary weight to freight, both of which are bad for the environment. Plastic pallets are more energy-intensive to produce and cannot be repaired, despite their lighter weight. The purpose of Life Cycle Assessment (LCA) study by Khan et al. (2021) was to compare the effects on the environment during the production, use, and disposal of wooden, plastic, and metal pallets. This research made use of both consequential life cycle assessment (CLCA) and attributional life cycle assessment (ALCA) approaches. Environmental impacts of the product system and associated systems that are predicted to change due to manufacturing, use, and disposal are studied by CLCA, while ALCA studies the effects of physical flows to and from the product's life cycle. The ALCA investigation covered the whole life cycle of a single pallet, from its creation from natural resources to its eventual disposal and subsequent emissions into the atmosphere and water supply. The ALCA investigation covered the whole life cycle of a single pallet, from its creation from natural resources to its eventual disposal and subsequent emissions into the atmosphere and water supply.

The ALCA study's system boundary includes raw material production, energy generation, pallet production, transportation, and end-of-life (EoL) treatment options like burning. Wooden or plastic pallets were included in the baseline scenario of the CLCA study, while the alternative scenario focused on the usage of wood-plastic composite (WPC) pallets to replace the same number of plastic pallets. Waste plastic and wood scraps that may have been recycled into WPC were also factored into the baseline scenario. The reference flow was established as the number of pallets needed to supply the customer with enough pallets for 1000 trips, and the functional unit for both ALCA and CLCA was 1000 trips. The 0:100 EoL technique with credit was used to attribute all environmental impacts to the product during the EoL phase while taking energy and material recovery into account. To reliably model the environmental impact, the CLCA used data on the marginal manufacturing technology of the product being substituted. Furthermore, in the study by Khan et al. (2022) mechanical recycling of waste plastic to produce plastic pallet or WPC pallet was compared to the chemical recycling and waste incineration.

9.2 Result

In the investigation, Khan et al. (2021) evaluated the environmental impacts of using pallets made of wood, plastic, and wood-plastic composite (WPC). Production, utilization, maintenance, and retirement are the four categories into which the ALCA findings were broken down. WPC pallets were found to have the smallest environmental impact across the board, except for Global warming potential (GWP), where hardwood pallets triumphed. In every category except for Eutrophication Potential (EP), plastic pallets were more damaging to the environment than their wooden counterparts. Pallet weight, energy used in production, the zero-burden approach to discard materials, and credit for substituting materials and energy were found to significantly affect ALCA outcomes. The zero-burden approach to wood and plastic waste in production, as well as the lack of environmental burden from the maintenance phase, allowed WPC pallets to demonstrate the lowest impact across the board. The production phase was the most affected by plastic pallets because of the amount of energy required to manufacture them. The use phase was most affected by wooden pallets due to the increased fuel consumption caused by their heavier weight. Wooden pallets were taken into account for upkeep primarily since plastic and WPC pallets cannot be fixed. Pallet weight, CO_2 emission factor, heating value, and biogenic carbon content all played a role in the EoL phase's aftermath. Because of their greater weight, wooden pallets were more likely to be incinerated, reducing their environmental impact during the EoL phase. Plastic pallets, on the other hand, had a higher heating value and recovered a greater quantity of energy after combusting.

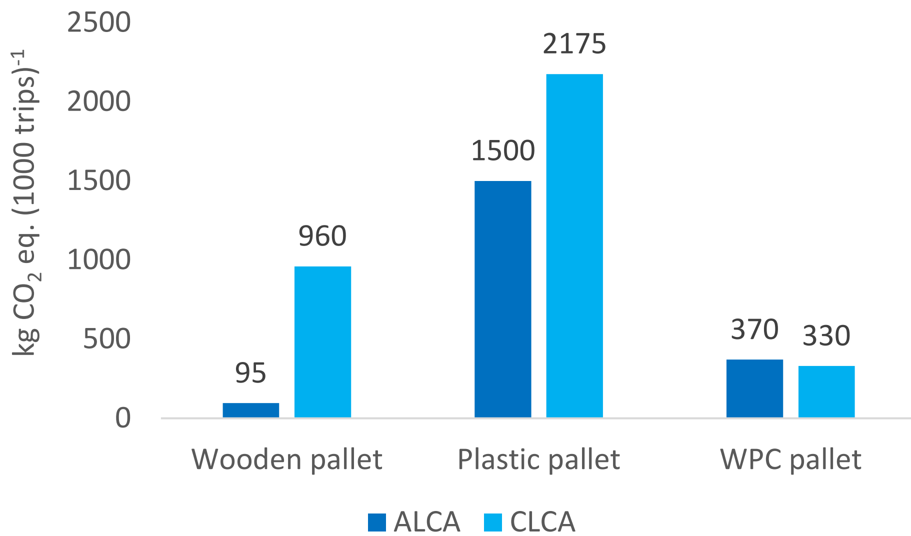

Figure 1. *GWP impact of ALCA and CLCA study* (Khan et al., 2021)

Factors including pallet weight, energy used in production, waste management strategy, and marginal heat and electricity sources were accounted for as the study assessed the environmental impact of several pallet designs using the CLCA method. According to the findings, WPC pallets caused the least harm to the environment overall. This was because of their reduced weight and hence fewer emissions throughout the usage phase in comparison to hardwood and plastic pallets. The study also accounted for electricity generated by wind and solar power as their respective marginal sources of electricity and heat, respectively. Compared to conventional heat production in Finland, biomass heat was found to result in fewer emissions. As compared to plastic pallets, which require more fossil fuels to produce, wooden pallets were found to reduce greenhouse gas emissions by 9 kg CO_2 equivalent for every thousand transports by a vehicle. Furthermore, the work by Khan et al. (2022) showed that mechanical recycling of plastic waste to WPC pallet showed better environmental performance compared to incineration or chemical recycling of plastic while direct mechanical recycling into pallet showed the lowest environmental impact.

9.3 Conclusion

Study by Khan et al. (2021) used a variety of approaches, including ALCA and CLCA, normalization calculations, and sensitivity analysis to investigate the environmental effects of wood, plastic, and WPC pallets. Weight, energy consumption during production, waste management strategy, and carbon-neutral technique for wood incineration were found to significantly affect the environmental impact of pallets. Due to lower fuel consumption during use and the zero-burden strategy for waste, WPC pallets achieved the lowest environmental consequences across the board in both ALCA and CLCA. Due to significant energy consumption in production, plastic pallets created from virgin materials had the greatest influence on the environment, whereas plastic pallets made from recycled plastic may need more study. The ALCA results showed that wooden pallets had the lowest GWP impact, however, the carbon-neutral method for wood incineration still needs more investigation.

10 Conclusions

The aim of this study was to facilitate the development of composite fibre products of mainly construction and demolition waste. Based on the screening of available waste fractions in South-Karelia it was found out that the almost 6000 tons of wood from the C&D industry were logged in the database, providing ample raw material for the pilot plant. Furthermore, the research findings showed the potential of the construction and demolition waste material as a raw material for secondary materials or products, for example in the manufacture of composites. The potential for modifying the material properties with different additives and fillers was also identified. Understanding the technical material requirements for recycled material is essential to ensure that product safety issues are met for a product made from recycled material. While the pilot trials provided valuable insights on the manufacturing subsystems, the commercialisation for mass production would benefit from the combination of large high speed presses, multi-molds, automated material flow and peripheral equipment to achieve the cost and productivity targets necessary for commercial viability. Beside the technical feasibility of WPC production, the evaluation of environmental performance analysis highlighted that incorporating CDW into WPC production can lower the negative effects of CDW management on the environment. The subsequent evaluation of WPC based pallet and comparison to wood and plastic pallet showed that in general level the WPC pallet achieved lowest environmental consequences. All and all the increasing market pull for sustainable materials provides and business opportunity for WPC products made through compression molding process from secondary raw materials.

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